AN ARGON COLLISIONAL-RADIATIVE MODEL APPLICATION TO HOLLOW-CATHODE

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ABSTRACT

The collisional-radiative model for an argon atom plasma is applied to analyse elementary processes in the emitter region of hollow cathode and predict the population distribution of excited states inside the emitter region. The modelling results show that the excited species derivate from the Boltzmann distribution. Based on the present model, the dominant kinetic processes of the excited states are investigated in order to better understand the performance of hollow cathode.

1. INTRODUCTION

Hollow cathodes have been studied extensively since the early 1930s due to their wide range of applicability in vacuum microelectronic devices, microwave tubes, lasers and materials processing. Over the past two decades hollow cathodes have also become critical components in many flight electric propulsion systems such as ion propulsion and Hall-effect thrusters. At power levels in the tens of kilowatts or higher cathode failure is one of the most critical obstacles to overcome before these thrusters can be employed routinely to long duration space missions [1]. Despite their long history and wide range of applicability that includes electric propulsion, detailed understanding of the driving physics inside orificed hollow cathodes remain elusive. The theoretical complexity associated with the multicomponent fluid inside the cathode, and the difficulty of accessing empirically this region, have limited our ability to design cathodes that perform better and last longer. Therefore, a collisional-radiative model is used to clarify the physics processes inside the hollow cathodes. A better understanding of the physics processes and the way in which the internal plasma develops would help to optimise cathode performance and increase the potential lifetimes of the thruster.

A collisional-radiative model applicable over a wide range of conditions [2, 3] was established for an argon atom plasma. In this paper a collisional-radiative model with less high level excited states than that of Vlcek is used. With the help of the numerical method, we can calculate the population coefficients determining the populations in all excited effective levels. This enables us to study the mechanisms by which these levels are populated under various conditions in a non-equilibrium argon plasma characterised by a set of different parameters.

The main aim of the present paper is firstly to check the reliability of our CR model by comparison with the experimental results of van der Mullen et al [4]. A further motivation for this study is our interest in understanding the mechanisms by which the excited levels are populated in hollow cathode of practical interest.

2. COLLISIONAL-RADIATIVE MODEL

The argon plasma system studied in this work is formed by ground state of atomic argon (Ar), excited states (4*s*, 4*p*, 3*d*/5*s*, 5*p* levels), argon ions (Ar^+) and electrons. The plasma is assumed electrical neutral and optically thin because the electron energy distribution function in the hollow cathode arc investigated is Maxwellian and the radiation trapping is negligibly small. Moreover, the energy distributions of particles are assumed Maxwellian. The kinetic processes include (a) electron impact excitation and de-excitation processes; (b) electron impact ionization and three-body recombination processes; (c) spontaneous emission; (d) radiative recombination.

$$Ar\,(i) + e(\varepsilon) \xleftrightarrow{C_{ij}^{e}} Ar\,(j) + e(\varepsilon - \varepsilon_{ij}) \qquad \text{(a)}$$

$$Ar\left(i\right)+e\left(\varepsilon\right)\xleftrightarrow{S_i^e} Ar^{+}+e\left(\varepsilon-\varepsilon_i\right)+e \qquad \text{(b)}$$

$$Ar\left(i\right)\xrightarrow{A_{ij}} Ar\left(j\right)+h\upsilon \qquad i>j \qquad \text{(c)}$$

$$Ar^{+}+e\xrightarrow{R_i} Ar\left(i\right)+h\upsilon \qquad \text{(d)}$$

where ε_{ij} and ε_i represent, respectively, the threshold energy of the transition *i--j* and the ionization energy from the *i*-th level. Atom-atom and ion-atom collisions have been neglected assuming that the electron-atom collision frequency dominates the kinetics.

Rate coefficients for electron-atom collisions are calculated from EEDF using the equation:

$$C_{ij}=\int_{E_{\min}}^{\infty} f\left(\varepsilon\right)\sigma\left(\varepsilon\right)v\left(\varepsilon\right)d\varepsilon \qquad (1)$$

where $f\left(\varepsilon\right)$ represents the EEDF, $\sigma\left(\varepsilon\right)$ the cross section of the transition between atomic levels *i* and *j*, $v\left(\varepsilon\right)$ the velocity of the electron of kinetic energy ε and E_{min} the threshold energy of the process. For the inelastic cross sections the analytical forms proposed by Drawin are particularly well adapted [2].

Cross-sections for super-elastic collisions and three-body recombination are calculated using the detailed balance principle [3]:

$$\sigma_{deexct}\left(i,\, j, E^{*}\right)=\frac{g_j}{g_i}\frac{E}{E^{*}}\sigma_{exct}\left(j,i,E\right) \qquad (2)$$

$$\sigma_{3b-recomb}\left(i,E^{*}\right)\frac{1}{n_e}=\frac{g_i}{2g_1^{+}}\frac{E}{E^{*}}\left(\frac{h^2}{2\pi m_e kT_e}\right)^{3/2}\sigma_{ioniz}\left(i,E\right) \qquad (3)$$

where g_i is the statistical weight of the *i*-th level and g_1^{+} is the statistical weight of the ion ground state, *h* the Planck constant, m_e the electron mass, *k* the Boltzmann constant and T_e the electron temperature. Eq. (3) is obtained assuming that energy after the ionization of the initially bound electron is zero. Radiative recombination rate coefficients have been calculated according to the work of Bultel [5].

According to the kinetic processes mentioned above and under conditions allowing the use of the quasi-stationary state model, the collisional-radiative model consists of a set of coupled linear equations

$$\sum_{j=2}^{N} a_{ij}n_j=-\delta_i-a_{i1}n_1 \qquad (4)$$

According to the method presented by Vlcek [2], the set of equations can be solved. The solution can be written as

$$n_i=r_i^{(0)}n_i^S+r_i^{(1)}n_i^B \qquad (5)$$

where n_i^S and n_i^B are the corresponding Saha population and Boltzmann population, respectively, $r_i^{(0)}$ and $r_i^{(1)}$ are the so-called CR coefficients relating the actual populations n_i to n_i^S and n_i^B respectively.

The numerical method developed allows us to calculate the coefficients $r_i^{(0)}$ and $r_i^{(1)}$ as functions of the following input parameters T_e, T_a, n_e and n_1.

3. RESULTS AND DISCUSSIONS

3.1 Comparison with experiment

Fig. 1 presents the 4*p*[1/2]$_1$ level population related to the corresponding Saha value as a function of the electron number density n_e at T_e=40600 K, T_a=11600 K, n_1=10^{19} m^{-3}. From the figure it can be seen that our result is consistent with the experimental data of van der Mullen [4] which can be used to validate the numerical method we adopted. With the increase of electron number densities, the uniform decrease of the calculated values of n_p/n_p^S as n_e^{-2} in the so-called 'excitation saturation phase' agrees well with the measured dependences. When the value of n_e becomes large enough the excited levels are considered to the regime of the partial local thermodynamic equilibrium.

In figure 2 we give our results for the coefficient $r_i^{(1)}$ of 4p[1/2]$_1$ level for various values of n_e at T_e=34800 K, T_a=3480 K, n_1=3.0×10^{18} m^{-3}. The values of the CR coefficients $r_i^{(1)}$ may be important for spectroscopic diagnostics of plasma, for example for the determination of the electron temperature T_e and the ground state atom population n_1 if the *n*th level is in the complete saturation phase. It appears that the $r_{4p}^{(1)}$ coefficient does not show a significant increase for 3×10^{19} m^{-3} < n_e < 10^{20} m^{-3} which agrees with earlier measurements [6].

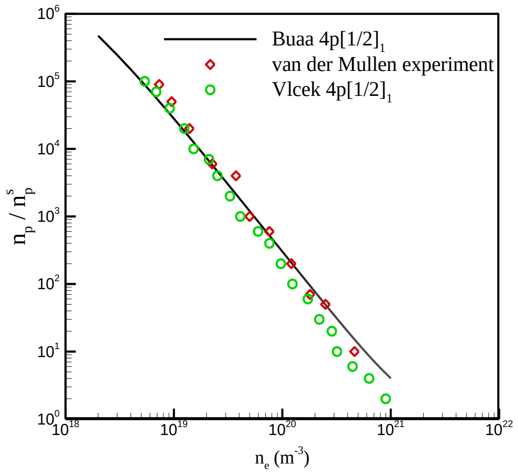


Fig. 1 the 4*p* level population related to the corresponding Saha value for various electron number densities n_e

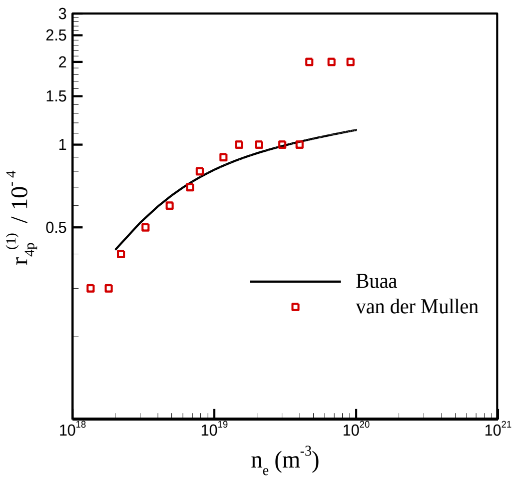


Fig. 2 the $r_{4p}^{(1)}$ coefficient for various electron number densities n_e

3.2 The calculation results of emitter region

The calculation results of the emitter region of hollow cathode [1] have been used as input parameters to clarify the excitation mechanisms of excited states. These parameters are as follows: (a) z=1 cm, T_e=1.6 eV, T_a=2000 K, n_e=2.5×10^{20} m^{-3}, n_1=2.4×10^{21}m^{-3}; (b) z=3 cm, T_e=1.3 eV, T_a=1300 K, n_e=3.0×10^{19} m^{-3}, n_1=7.5×10^{21} m^{-3}, where z stands for the distance away from the orifice entrance.

Figure 3 shows the distribution of excited states at the emitter region where z=1 cm. From this figure it can be concluded that the plasma is in an ionized state. The distribution of excited states deviates from the Boltzmann distribution. The high-lying level states come closer the Saha distribution. Figure 4 gives the distribution of excited states at z=3 cm where the ionization degree is lower than that of orifice entrance. From this figure we can see that radiation processes become important.

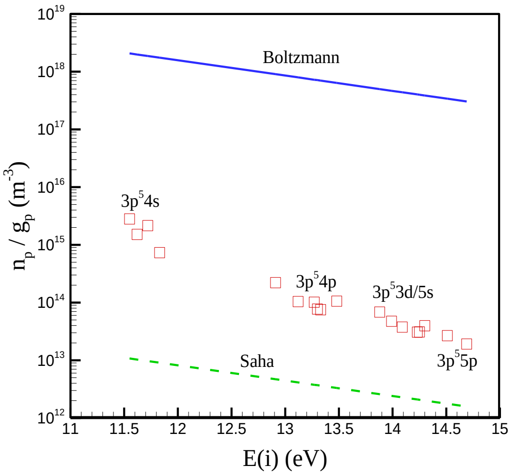


Fig. 3 the distribution of excited states at the emitter region of hollow cathode (z=1 cm)

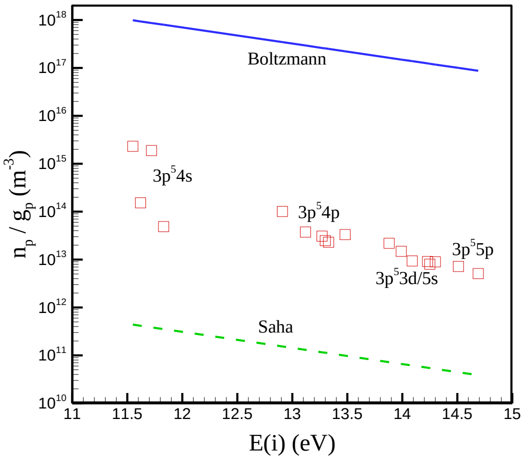
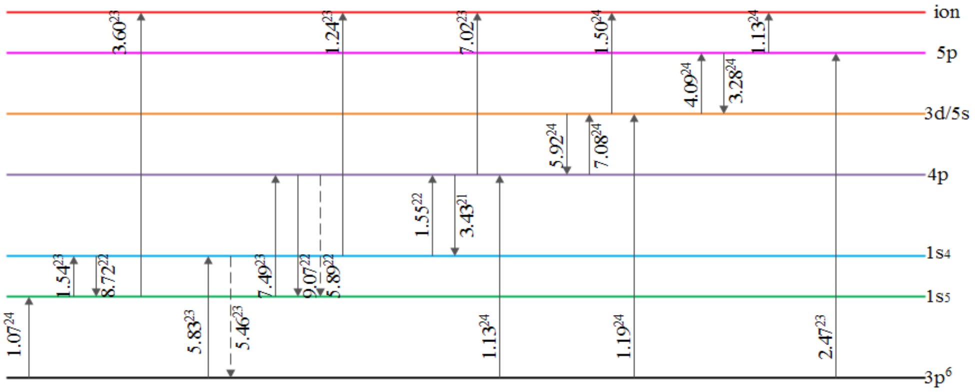


Fig. 4 the distribution of excited states at the emitter region of hollow cathode (z=3 cm)

Figure 5 presents the dominant kinetic processes at z=1 cm and z=3 cm respectively. The plasma is in an ionizing state. The main production mechanisms of excited states are electron impact excitation processes of ground state atoms and the step excitation processes from the adjacent level. The main destruction mechanisms of excited states are electron impact ionization processes and electron collisional de-excitation to the adjacent low-lying level. From this figure it can be found that electron collisional ionization processes for high-lying level states are the main ionization channel. Radiation processes become important at the distance where is away from the orifice entrance.



(z=1 cm)

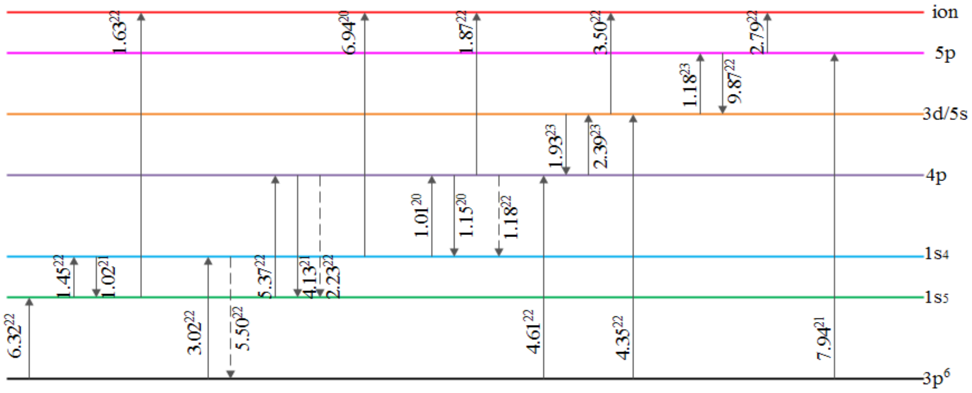


Fig. 5 the main kinetic processes at the emitter region (*z*=3 cm)

4. CONCLUSIONS

This CR model provides a qualitatively picture of the processes determining the populating mechanism in the emitter region of hollow-cathode where the electron energy distribution function is Maxwellian and the radiation trapping is negligibly small. It is found that the distribution of excited states deviates from the Boltzmann distribution. Radiation processes have great effects on the distribution. The electron impact excitation processes of ground state become important due to the large densities of ground state atom. Electron collisional ionization processes for high-lying level states are the main ionization channel. What's more, the step processes between adjacent levels are the main excitation mechanism.

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