

Influence of dust particles on ionization and excitation in neon dc discharge

V V Shumova, D N Polyakov and L M Vasilyak

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia

E-mail: shumova@ihed.ras.ru

Abstract. The influence of dust particles on the concentration of metastable neon atoms and ionization was investigated using the developed drift/diffusion model for plasma of positive column of glow discharge. The detailed de-excitation in neon was considered. In addition to usual plasma losses in dusty plasmas, the quenching of metastable atoms on dust particle surface was considered. The strong influence of dust particles on the ionization rate and concentration of metastable neon atoms in a positive column of glow discharge is shown to result from the change in the longitudinal electric field strength.

1. Introduction

Microparticles can be used in a variety of technological and medical applications. They may be maintained in a reaction volume in different types of plasma traps [1, 2] or in dynamic traps, e.g. quadrupole Paul trap [3]. In plasma traps for microparticles (in dusty plasmas), the recombination of ions and electrons on a dust particle surface is studied in detail [4], but the quenching of excited atoms including metastable atoms, is much less understood.

Excited atoms play important role in plasma processes; their concentrations determine the radiative properties of plasmas. Because of high concentration of metastable atoms, especially in plasmas of noble gases, their quenching on a surface of dust particles is the important channel of plasma losses in dusty plasmas. In addition, excited atoms produce free electrons participating in the processes of step-wise ionization and chemi-ionization. Despite a numerous experimental observations of effects in concentration of metastable atoms caused by dust particles in dusty plasmas [5–9], this question is almost not considered theoretically.

The widely used approach to the numerical simulation of plasma of the positive column consists in the solution of the Poisson equation and fluid equations for heavy components and nonlocal kinetic equation for electrons. By this way, the results on the metastable atom influence on parameters of glow discharge in pure argon were obtained in [10], and the metastable atom concentration was simulated in the nonuniform two-dimensional positive column in pure neon [11]. The influence of dust particles on plasma of the positive column of glow discharge was simulated by the same procedure in argon [12], but the excitation and step-wise ionization were not considered.

Hence, the influence of dust particles on the excitation and hence, on the ionization in dusty plasmas seems to deserve further investigation, especially in a dc discharge. The aim of the present study was to simulate the dust particle influence on the concentration of metastable



neon atoms, and further, the ionization in a positive column of glow discharge, depending on discharge conditions. As the basic model, we have used the drift/diffusion model of the positive column of glow discharge that proved the reliability for simulations of dc discharges with dust particles in air [13, 14] and neon [15, 16]. In this study, for the more accurate simulation of excited atom concentration and ionization, the model was developed in neon, considering the de-excitation of metastable atoms in more detail, in particular with the account of metastable atom quenching to a resonant state.

2. Model formulation

As a model we consider neon plasma consisting of electrons, ions, ground state neon atoms and metastable neon atoms of $1s$ configuration (in Paschen's notation) with the energy of 16.62 eV. The ionization by single electron collision with neon atom in the ground state, and the step-wise ionization through the metastable state is considered. The later process is important for the adequate simulation of the plasma ionization degree at low energies of electrons. Molecular ions and negative ions were neglected.

We describe neon plasma in frames of diffusion/drift approximation. We consider the positive column with uniform gas density and apply Schottky theory, basing on the idea of ambipolar diffusion of ions and electrons towards the tube walls in quasi-neutral plasma. The electric field of discharge is represented as a combination of invariable longitudinal component E_l , and self-consistent radial component E_r determined by radial gradient of the field potential.

The radial flow densities of ions, electrons and metastables J_e , J_i and J_m result from the superposition of drift and diffusion constituents. In the regime of ambipolar plasma J_e and J_i are equal. For metastables the drift term is zero. The radial flows $J_{i,m,e}$ submit to the equation of continuity with the corresponding source terms $q_{i,m,e}$ of species:

$$\text{div} J_{i,m,e} = q_{i,m,e}, \quad (1)$$

$$q_{i,e} = k_i n_a n_e + k_{im} n_m n_e + k_{mm} n_m^2 - n_d J_{d\ i,e}, \quad (2)$$

$$q_m = k_{exc} n_a n_e - k_{im} n_m n_e - 2k_{mm} n_m^2 - k_{qa} n_m n_a - k_{qe} n_m n_e - k_r n_m n_e - n_d J_{dm}. \quad (3)$$

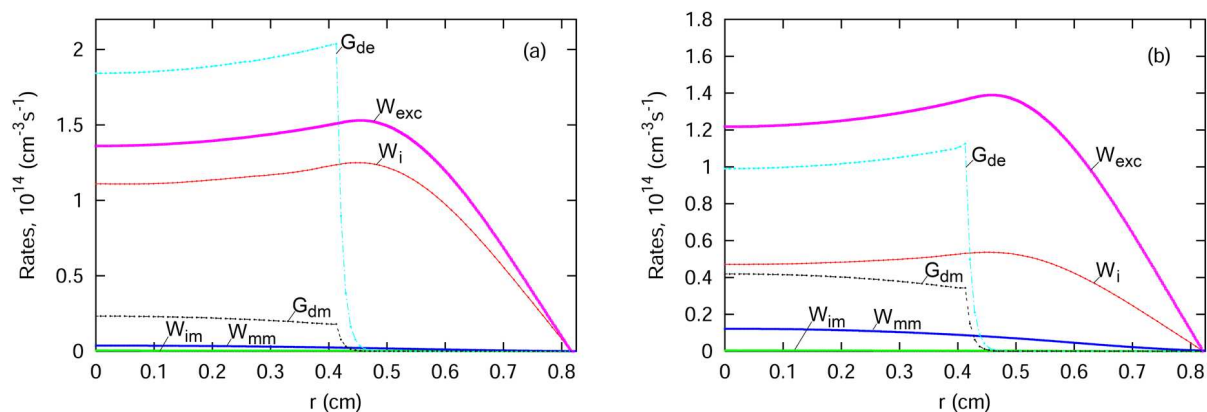
Here $n_{i,m,e,d}$ are the ion, metastable, electron and dust particle concentrations and $J_{d\ i,m,e}$ the flows of ions, metastables and electrons to the dust particle surface. In equations 2,3 k_i and k_{im} are the rate coefficients of ionization from the ground and metastable states of neon correspondingly, k_{mm} is the rate coefficient of chemi-ionization (metastable pooling), k_{exc} is the rate coefficient of excitation of metastable state from the ground, k_{qe} and k_{qa} are the rate coefficients of the metastable quenching in collisions with electrons and atoms, k_r is the rate coefficients of the metastable quenching to resonant state.

Table 1 shows the mentioned above processes in neon plasma, the corresponding rate coefficients and the values of energy exchange per collision ΔH .

J_{de} and J_{di} were calculated using the collision enhanced collection (CEC) model for dust particle charging in the weakly collisional plasma developed in [23, 24] and equal to each other as far as a dust particle is supposed to be at a floating potential. J_{dm} is calculated as $J_{dm} = \pi a^2 n_m V_m$, where a is the dust particle radius and V_m the metastable thermal velocity $V_m = (8T_m/\pi m_m)^{1/2}$. Ion, excited (metastable) atom and electron distributions meet the zero boundary condition at the tube wall coordinate R : $n_{i,m,e}|_{r=R} = 0$, and the boundary condition following from the symmetry of the discharge $(dn_{i,m,e}/dr)|_{r=0} = 0$ on the axis. The last equations are equation of plasma electro neutrality and integral equation for the integrated value of discharge current I . Solving the formulated boundary problem with desired dust particle distribution $n_d(r)$ and discharge current we have found the radial distributions of ions, metastables and electrons and the electric field. In more detail the theoretical background and limitations of this approach were described in [13,14]. The temperatures of atoms and ions were

Table 1. Important collision processes in neon discharge at low pressure.

Process	Reaction	ΔH , eV	Rate coef.	Ref.
Ground state ionization	$Ne + e^- \rightarrow 2e^- + Ne^+$	21.56	k_i	[17–19]
Step-wise ionization	$Ne^* + e^- \rightarrow 2e^- + Ne^+$	4.94	k_{im}	[17–19]
Chemi-ionization	$2Ne^* \rightarrow Ne^+ + Ne + e^-$	-	k_{mm}	[20]
Ground state excitation	$Ne + e^- \rightarrow Ne^* + e^-$	16.62	k_{exc}	[17–19]
Quenching by electrons	$Ne^* + e^- \rightarrow Ne + e^-$	-16.62	k_{qe}	[21]
Quenching to resonant	$Ne^* + e^- \rightarrow Ne^r + e^-$	-	k_r	[21]
Quenching by atoms	$Ne^* + Ne \rightarrow 2Ne$	-	k_{qa}	[22]

**Figure 1.** Rates of plasma processes in a positive column of glow discharge in neon with $I=0.5$ mA in presence of dust particles with concentration $2 \times 10^5 \text{ cm}^{-3}$ for various values of neon pressure: (a) 0.35 Torr and (b) 0.9 Torr.

supposed to be 295 K, the mean electron energy and transport coefficients were obtained using the SIGLO Database [17–19] and the electron Boltzmann equation solver BOLSIG+ [25]. The mobility of metastables was extrapolated using data [26].

3. Results and discussion

The simulations were carried out in the next typical low pressure gas discharge conditions, where was observed the formation of the dense dust structures influencing the parameters of neon discharge [15]: the cylindrical discharge tube of 16.5 mm i.d., neon pressure P from 0.3 to 1 Torr and discharge current I up to several mA. The radial distribution of dust particles in the dust structure was defined by a step function with exponentially decaying blurring at the edges, described by dust particle concentration n_d on the axis of the discharge tube and the size of dust structure $r_d(r) = R/2$, typical for experiments [15]. The dust particles size was $2.55 \mu\text{m}$.

The concentrations of plasma particles in dusty plasma are governed by the competition of processes represented in table 1. Their rates depend both on the discharge parameters and on dust particle concentration. Figures 1(a) and 1(b) represent the values of the rates of plasma processes W_i , W_{im} , W_{mm} and W_{exc} (denoted correspondingly to their rate constants from table 1), and the rates of electron losses $G_{de} = n_d J_{de}$ and metastable atom losses $G_{dm} = n_d J_{dm}$ on dust particles, for two values of gas pressure. Other plasma processes have the lower rates under our conditions.

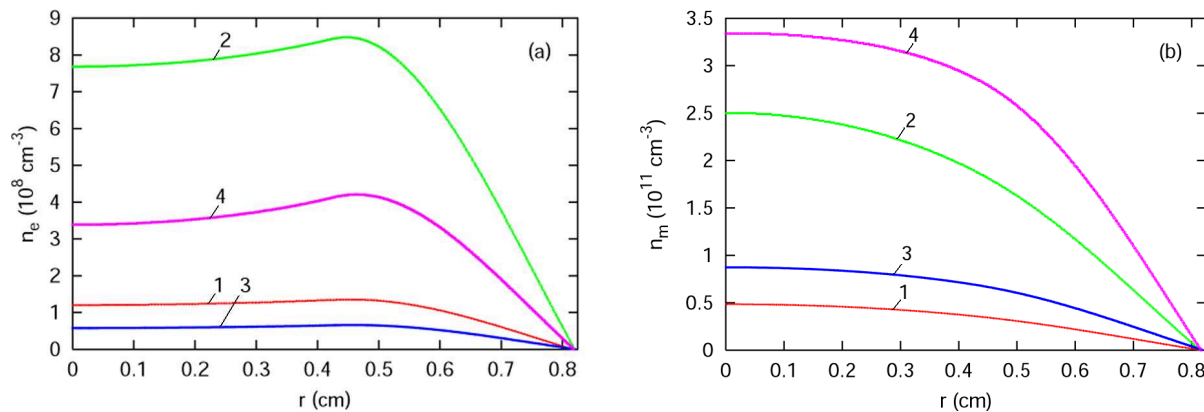


Figure 2. Concentrations of (a) electrons and (b) metastable atoms in a positive column of glow discharge in neon in presence of dust particles with concentration $2 \times 10^5 \text{ cm}^{-3}$ at various values of pressure and discharge current: 0.35 Torr, 0.5 mA (1, red lines); 0.35 Torr, 3 mA (2, green lines); 0.9 Torr, 0.5 mA (3, blue lines); 0.9 Torr, 3 mA (4, pink lines).

The rate of the ground state excitation, directly producing metastable atoms, principally determines the metastable atom concentration both at lower (0.35 Torr) and at higher (0.9 Torr) gas pressure. At higher pressure, the rates of metastable atom losses G_{dm} and chemi-ionization relatively increase, the predominant plasma process becomes the excitation from the ground state.

Figures 2(a) and 2(b) represent the radial profiles of concentrations of electrons and metastable atoms for four sets of gas discharge conditions with the same dust particle concentration $2 \times 10^5 \text{ cm}^{-3}$, as in figure 1.

The electron concentration depends mostly on discharge current, while the metastable atom concentration on gas pressure. Note that the electron profiles are visibly depleted in the center of the discharge tube due to losses on dust particle surface. In opposite, the metastable atom profiles become more radially uniform than the Bessel profile in pure neon [15]. The values of the longitudinal electric field strength E_l for cases represented in figure 2 are 5.51 V/cm for 0.35 Torr and 0.5 mA, 5.4 V/cm for 0.35 Torr and 3 mA, 11.18 V/cm for 0.9 Torr and 0.5 mA, and 10.81 V/cm for 0.9 Torr and 3 mA. In pure neon, the values of E_l are lower for the same discharge conditions: 4.3, 4.05, 7.22 and 5.85 V/cm respectively. Figure 3 represents the ratio of concentrations of metastable atoms and electrons $Q_m(n_d) = n_m(n_d)/n_e(n_d)$ in neon plasma with various concentration of dust particles, in relation to $Q_m(0) = n_m(0)/n_e(0)$ in pure neon. One can see that $Q_m(n_d)$ increases with dust particle concentration and may be about few times greater compared to the value $Q_m(0)$ in pure neon. It is this effect that determines the increase in population of Ar metastable levels in plasma with growing inside [6,7] or introduced outside [8,9] dust particles compared to pristine plasmas.

The increasing partial concentration of excited atoms in dusty plasma, determines the increase of losses of plasma excitation on dust particles. The conclusion on the efficiency of step-wise ionization in presence of dust particles may be derived if we compare the partial rate of the ionization through the preliminary excitation of metastable level (including step-wise and chemi ionization) and losses of excited atoms on dust particles. The partial rate of the non-direct ionization i.e. the sum of partial rates of step-wise and chemi-ionization is $R_i = (W_{im} + W_{mm})/(W_i + W_{im} + W_{mm})$, the partial rate of losses of excitation of metastable atoms on dust particles in total plasma losses on dust particles, that may proceed also through electrons, is $R_d = J_{dm}/(J_{de} + J_{dm})$. These values are represented in figure 4. Figure 4 shows

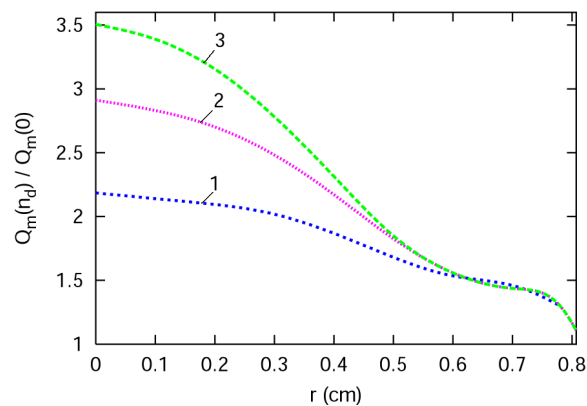


Figure 3. Ratio Q_m of concentrations of metastable atoms and electrons in dusty plasmas, normalized to $Q_m(0)$ in pure neon at 0.9 Torr and 3 mA, for various values of dust particle concentration: $1 \times 10^5 \text{ cm}^{-3}$ (1, blue line), $2 \times 10^5 \text{ cm}^{-3}$ (2, pink line), $4 \times 10^5 \text{ cm}^{-3}$ (3, green line).

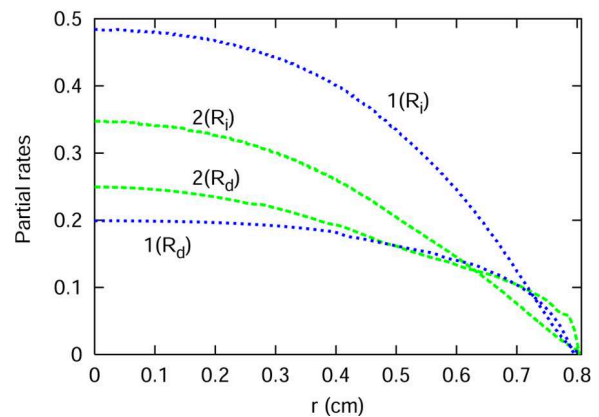


Figure 4. Partial rates of non-direct ionization R_i and losses of excitation of metastable atoms on dust particles R_d at 0.9 Torr, 3 mA for various values of dust particle concentration: $1 \times 10^5 \text{ cm}^{-3}$ (1, blue line), $4 \times 10^5 \text{ cm}^{-3}$ (2, green line).

that the partial rate of ionization with the participation of preliminary excited metastable level is higher in the main part of the discharge cross-section. Evidently, this result follows from the strong dependence of electron losses on dust particles versus the electron temperature (implicitly, versus the electric field strength). This means that the correct consideration of excitation and quenching is necessary in dusty plasmas, where excited atoms may play even more important role than in pure gases. As far as metastable atoms give additional electrons in processes of step-wise and chemi-ionization, they may have influence upon the dust particle charging, that should be taken into consideration during the simulation of plasma traps for dust particles.

4. Conclusion

Dust particles change not only plasma losses in a plasma bulk, but also the relative rates of excitation and ionization channels in plasma. In this study the analysis of plasma ionization and losses in presence of dust particles is carried out. The detailed consideration of excitation and quenching enabled us to compare the efficiencies of ionization mechanisms in neon dc discharge.

The rates of governing plasma processes in neon dusty plasma depend both on discharge pressure, current and on the dust particle concentration. The concentration of metastable atoms strongly depends on the rate of the ground state excitation determined by the electron temperature. At constant discharge current, the electron temperature is higher in presence of dust particles simultaneously with the longitudinal electric field strength, therefore the dust particles strongly influence on the concentration of metastable neon atoms in a positive column of glow discharge.

The quenching of metastable atoms on dust particles may be more intense than the spending of their excitation in other plasma processes. Nevertheless, dust particles increase the relative concentration of metastable atoms versus electrons in neon dusty plasma in comparison with the pure neon discharge with the same discharge parameters, up to few times.

The sum of partial rates of step-wise and chemi-ionization is higher than the partial rate of losses of excitation of metastable atoms on dust particles. Giving additional electrons in these processes, metastable atoms may have influence upon the dust particle charging, that should

be taken into consideration during the simulation of plasma traps for dust particles in further studies.

Acknowledgments

This work was supported by the Russian Science Foundation (grant No. 14-50-00124).

References

- [1] D'yachkov L G 2015 *High Temp.* **53** 613–621
- [2] D'yachkov L G 2015 *Tech. Phys. Lett.* **41** 602–605
- [3] Lapitskiy D S, Filinov V S, Deputatova L V, Vasilyak L M, Vladimirov V I and Pecherkin V Y 2015 *High Temp.* **53** 1–8
- [4] Fortov V E and Morfill G E 2009 *Complex and Dusty Plasmas. From Laboratory to Space* (Boca Raton: CRC Press)
- [5] Bouchoule A and Boufendi L 1994 *Plasma Sources Sci. Technol.* **3** 292–301
- [6] Stefanovic I, Sadeghi N and Winter J 2010 *J. Phys. D: Appl. Phys.* **43** 152003
- [7] Do H T, Sushkov V and Hippler R 2009 *New J. Phys.* **11** 033020
- [8] Do H T, Kersten H and Hippler R 2008 *New J. Phys.* **10** 053010
- [9] Mitic S, Pustynnik M Y and Morfill G E 2009 *New J. Phys.* **11** 083020
- [10] Bogdanov E A, Kudryavtsev A A, Tsendin L D, Arslanbekov R R, Kolobov V I and Kudryavtsev V V 2004 *Tech. Phys.* **49** 698–706
- [11] Zobnin A V, Usachev A D, Petrov O F and Fortov V E 2014 *Phys. Plasmas* **21** 113503
- [12] Sukhinin G I, Fedoseev A V, Antipov S N, Petrov O F and Fortov V E 2013 *Phys. Rev. E* **87** 013101
- [13] Polyakov D N, Shumova V V, Vasilyak L M and Fortov V E 2010 *Phys. Scr.* **82** 055501
- [14] Polyakov D N, Vasilyak L M, Shumova V V and Fortov V E 2011 *Phys. Lett. A* **375** 3300–3305
- [15] Vasilyak L M, Polyakov D N and Shumova V V 2013 *Contrib. Plasma Phys.* **53** 432–435
- [16] Shumova V V, Polyakov D N and Vasilyak L M 2014 *Plasma Sources Sci. Technol.* **23** 065008
- [17] Pitchford L C and Boeuf J P 2013 *SIGLO Data Base* (<http://www.lxcat.laplace.univ-tlse.fr/>)
- [18] Meunier J, Belenguer P and Boeuf J P 1995 *J. Appl. Phys.* **78** 731
- [19] Alves L L, Bartschat K, Biagi S F, Bordage M C, Pitchford L C, Ferreira C M, Hagelaar G J M, Morgan W L, Pancheshnyi S, Phelps A V, Puech V and Zatsarinny O 2013 *J. Phys. D: Appl. Phys.* **46** 334002
- [20] Sheverev V A, Stepaniuk V P and Lister G G 2002 *J. Appl. Phys.* **92** 3454–3457
- [21] Malinin A N 1998 *Laser Phys.* **8** 395–406
- [22] Phelps A V and Molnar J P 1953 *Phys. Rev.* **89** 1202
- [23] Khrapak S A and Morfill G E 2006 *Phys. Plasmas* **13** 104506
- [24] D'yachkov L G, Khrapak A G, Khrapak S A and Morfill G E 2007 *Phys. Plasmas* **14** 042102
- [25] Hagelaar G J M and Pitchford L C 2005 *Plasma Sources Sci. Technol.* **14** 722
- [26] Eiletskii A V, Palkina L A and Smirnov B M 1975 *Transport Phenomena in Weakly Ionized Plasma* (Moscow: Atomizdat)