Non-local character of negative glow emission of a low pressure glow discharge

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Abstract. A beam electron energy distribution function (BEEDF) in the cathode regions of a low-pressure glow discharge in helium was calculated using a Monte-Carlo technique. Based on the obtained data on the distribution of the BEEDF along the discharge length, the excitation rate of the 1s3p 1P level was calculated assuming that the direct electron excitation of helium atoms from the ground state takes place. It is shown that the calculated excitation rates of the 1s3p 1P level along discharge path are in good agreement with the experimentally measured emission distribution of the 501.6 nm helium spectral line.

1. Introduction
It is known that the local values of the electric field in the region of the negative glow of a discharge are not able to compensate the loss of charged particles due to volume and wall recombination by the corresponding nucleation processes [1]. The local values of the electric field in the negative glow (NG) region is so small that a positive column should have been formed immediately after the formation of a cathode layer without the NG region. However, at low pressures, the NG region is the largest region of a glow discharge. The main source of ionization in this area is a beam of high-energy electrons formed in the cathode layer of a glow discharge. The localized strong electric field near the cathode surface [2] leads to formation of a not numerous group of fast electrons, propagating further along the discharge path and responsible for the formation of a NG region [3].

At beam propagation along the discharge path in addition to ionization collisions the electrons also excite atoms which leads to optical emission. If other atom excitation processes are insignificant, the distribution of intensity of the spectral lines emission will characterize the averaged energy and concentration of the beam electrons along the NG path of the glow discharge. This paper compares the calculated radiation profile for the 501.6 nm helium spectral line with the measured one. The calculation of the spectral line emission profile is made on the basis of the beam electron energy distribution function (BEEDF) calculated by the Monte Carlo method along the discharge path. At the calculation of BEEDF, the electrons energy dissipation due to inelastic collisions and recombination of the beam electrons on the wall of the discharge chamber due to scattering are taken into account.
2. Experimental setup
A principal scheme of experimental setup is shown in figure 1. Gas discharge chamber 1 is made of quartz tubes with the inner diameter $R = 44$ mm and the total length of 45 cm. The helium was fed into the discharge chamber from balloon 2 through a needle valve and was continuously pumped out by a fore vacuum pump 3. The discharge current and voltage were measured with an ammeter 4 and a high-voltage voltmeter 5, respectively. The discharge chamber was placed on the rail and could move along its axis $x$. Using a quartz lens 6, the emission from the discharge was focused on the entrance slit of the monochromator (MDR-23) 7 with diffraction grating of 600 lines/mm. The optical set-up was adjusted so that emission from the whole cross-section of the discharge with 2 mm long illuminates the entrance slit of the monochromator. For the cathode fall region length $L_{CF}$ measurements the discharge photos were taken and then processed by the PC with an accuracy of $\pm 0.5$ mm.

3. Model of negative glow emission
To find the beam electron energy distribution function the trajectories of the electrons motion were calculated starting from the cathode surface at $x = 0$. The calculation space was divided into two regions. Axial component of electric field $E_x$ in the first region corresponding to the cathode fall region was defined as a linearly decreasing in accordance with the measured values of $L_{CF}$ and the voltage drop on the discharge $U_d$ which assumed to be equal to the voltage drop on the cathode sheath. The second computation region corresponding to the NG was specified without an axial electric field $E_x = 0$. The radial component of the electric field was not considered for both computational regions.

The determination of BEEDF, $f(\varepsilon, x)$ was performed in the process of the electron path calculation and consisted in finding the number $J$ of crossings the plane $(y, z)$ by electrons having energy within the interval $(\varepsilon, \varepsilon + \Delta \varepsilon)$ [4]:

$$f(\varepsilon, x) = \sum_j \frac{\varphi_{0e}}{N_{it} \Delta \varepsilon} \frac{1}{|V| \cos \Theta_j}$$

Here, $\varphi_{0e}$ is the electron flux rate on the cathode, $N_{it}$ is the total number of electrons escaped from the cathode, $|V| = (2\varepsilon/m)^{1/2}$ is the modulus of velocity vector of an electron, and $\Theta_j$ is the angle between the axis $x$ and $V$ at the moment of crossing the plane $(y, z)$.

A path of electron motion between collisions was calculated in accordance with the second Newton law. The free path length $\lambda_{tot}$ was calculated in the following way:

$$\int_{s_0}^{s_0 + \lambda_{tot}} N \sigma_{tot}(\varepsilon(s)) ds = -\ln(1 - R_{01}),$$

where $s_0$ is the initial position of the electron on curve $s$, $N$ is the gas density, $\sigma_{tot}$ is the total collision cross section, $\varepsilon$ is the kinetic energy of the electron, and $R_{01}$ is the random number from the interval $(0, 1)$. A type of collision was determined randomly in proportion to the contribution of the process cross

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*Figure 1. Experimental setup:*
1 – gas discharge chamber,
2 – gas balloon,
3 – fore vacuum pump,
4 – ammeter,
5 – voltmeter,
6 – quartz lens,
7 – monochromator.
section under study. The elastic collisions of an electron with the neutral gas, the ionization by the electron impact from the ground state, and the excitation of the $1s2p\,^1P$ level of the helium atom were taken into account. Dependences of total cross sections of elastic, ionization, and excitation collisions on the energy of an incident electron are taken from [5–8].

When the elastic electron–atom collision occurred, the electron scattering by the angle $\theta$ was taken into account, in this case its energy reduced by the value of $\Delta \varepsilon_{el}$:

$$
\Delta \varepsilon_{el} = -\frac{2m}{M}(1 - \cos \theta),
$$

where $m/M$ is the ratio of electron to helium atom masses. The elastic scattering angle $\theta$ was determined in accordance with the experimental data on differential cross section [9–11]. At the ionization collision, the energy of primary electron was decreased by the sum of the ionization potential and the secondary electron energy determined randomly in accordance with differential cross section, taken from [12]. In view of the absence of necessary experimental data on the double differential cross section of scattering in ionization, the scattering angle $\theta_1$ of the incident electron and the ejected angle $\theta_2$ of the secondary electron were defined as follows [3]:

$$
\theta_1 = \pm \arccos \left( \frac{\varepsilon_1}{\varepsilon_1' - I_0} \right)^{1/2},
$$

$$
\theta_2 = \theta_1 \pm \frac{\pi}{2},
$$

where $\varepsilon_1$ and $\varepsilon_1'$ are the energies of primary electron before and after the ionization, respectively. If the excitation of the $1s2p\,^1P$ level take place the electron energy was decreased by the excitation potential $I_{exc} = 21.21$ eV.

The calculation of the trajectory of the electron movement was stopped if the sum of potential and kinetic energies of the electron become less than the excitation potential of $1s2p\,^1P$ level or the electron got out beyond the limit of the computational region ($x^2 + z^2 \geq R^2$). If the sum of potential and kinetic energies of the secondary electron was larger than $I_{exc}$, it also took part in forming the BEEDF, and the calculation of its path was performed with the relevant initial data. The initial number of electrons, for which the calculation of the trajectories of movement was performed, amounted to $N_{it} = 10^5$. The BEEDF discretization in energy was specified with $\Delta \varepsilon = 1$ eV. A more detailed description of the model used was given in [4].

Using the obtained result of BEEF calculations, the production rate of the $1s3p\,^1P$ helium level with the ionization potential $I_k = 23.9$ eV and the excitation cross section $\sigma_k$ which is excited from the ground state was calculated:

$$
Z_k = C \cdot N \int_{I_k}^{U_j} \epsilon f(\epsilon, x)\sigma_k(\epsilon) d\epsilon.
$$

4. Results and discussion

The comparison of the production rate of the $1s3p\,^1P$ level calculated by formula (1) and the experimentally measured emission of 501.6 spectral line ($1s2s\,^1S - 1s3p\,^1P$) along the discharge path is shown in fig. 2 at the gas discharge pressure of 30 Pa and the discharge current of 5 mA. It is seen that the glow discharge emission demonstrates the presence of the main cathode regions. In the result of acceleration in the electric field the electrons energy is increased. The emission intensity of the 501.6 nm line is increased from the cathode surface ($x \approx 0$ cm) and reaches its maximum value at the cathode glow region ($x \approx 0.6$ cm) for both the calculated and the measured dependence. The further increase in the electron energy leads to a decrease in the excitation cross section. The emission intensity of the 501.6
nm line is decreased. However, at the end of the cathode layer region, the secondary electrons arising in the deeps of the cathode layer gain enough energy to excite a $1s3p\ ^1P$ level and begin to make a noticeable contribution to the formation of the line emission. The intensity of the 501.6 nm line is increased again. At the end of the cathode layer region an electron avalanche is formed and the NG region appears ($x \approx 2.2$ cm). It can be seen from fig. 2 that the calculated emission intensity increases in this region not as much as the experimental dependence.

This difference in the behavior of the curves can be explained by the contribution to the emission produced by the main group of electrons which is not taking into account in the presented model. At the beginning of the NG region, the temperature of the electrons of the main group is enough to excite the $1s3p\ ^1P$ level from the metastable states. The absence of an electric field in the NG region leads to cooling of the main group of electrons along the length of the discharge [13]. The contribution of the main group of electrons to the excitation of the $1s3p\ ^1P$ level is gradually decreased. The beam electrons become the only source of excitation at the end of the NG region.

The discharge voltage $U_d$ and the length of the cathode layer $LC_F$ are decreased with an increase of the discharge pressure (Fig. 3). The maximum of the emission intensity of the 501.6 nm line is moved into the NG region. This fact can be explained a higher of ionization degree than in the case of $p = 30$ Pa. The contribution of the main group of electrons to the formation of the line emission is increased. The relaxation of the beam of the fast electrons along the discharge path is accelerated because the frequencies of elastic and inelastic collisions are increased.

Figure 2. Comparison of a calculated production rate of the $1s3p\ ^1P$ level and measured relative intensity of the 501.6 nm line emission. He, $p = 30$ Pa, $I_d = 5$ mA, $U_d = 1400$ V, $LC_F = 2.16$ cm.
Figure 3. Comparison of a calculated production rate of the 1s3p $^1P$ level and measured relative intensity of the 501.6 nm line emission. He, $p = 70$ Pa, $I_d = 5$ mA, $U_d = 800$ V, $L_{CF} = 1$ cm.

Conclusions
The calculated excitation rates of the level using the BEEDF which is evaluated by the Monte-Carlo technique are in a good agreement with the experimentally measured emission distribution of the 501.6 nm line along the glow discharge path. It is shown that in the cathode glow region the beam is the main source of excitation of the 1s3p $^1P$ level from the 1s2s $^1S$ atomic ground state. At the beginning of the NG region, the contribution of secondary electrons with energies less than $I_{ext}$ to the production rate of the 1s3p $^1P$ level due to the excitation of metastable levels should be taken into account. At the end of the NG region, the mean energy of the beam electrons is decreased, but it still enough for the main contribution to the formation of the emission of the 501.6 nm line.

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