POLARIZATION DIAGNOSTICS OF HELIUM PLASMA RADIATION IN AN ELECTRIC GAS DISCHARGE OF THE BEAM TYPE

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This paper presents some results of theoretical and experimental studies of the electrostatic field influence on the radiation and collision processes in a gas discharge plasma. Formulas derived for describing angular and polarization characteristics of radiation of atoms due to dipole transition from Stark state are presented. Formula for cross section of the atomic excitation by electrons is derived and some regularities in the electric field influence on the amplitude of inelastic scattering are revealed. Using formalism of polarization tensors the formulas are derived for the degree of linear polarization of plazma emission in the electric field at the anisotropic pump by an electron beam. The obtained formulas made a basis for a technique for determining the electric field strength and populations of Stark states of atoms.

Experimental results on measuring the degree of linear polarization of the helium plasma emission in a gas discharge of the beam type have shown a good qualitative agreement with the results of theoretical calculations.

Advances reached in recent years in developing methods for determining the collision cross sections and the experimental techniques have made a new method of polarization diagnostics practicable.[1] This method is based on measurements of polarization characteristics and the angular distribution of plasma radiation which bear information about anisotropic processes in plasma.

As known[2] these processes result in the polarization of atomic states what, in turn, leads to an anisotropic angular distribution and polarization of radiation of the plasma spectral lines. The anisotropic pump (electron and light beams[3,4]), anisotropic relaxation processes (ion drift in the gas discharge plasma and the transfer of the resonance radiation[5,6]), and external fields cause the polarization of atomic states.

The mechanism of polarization of isolated atomic states has been well studied. Some methods of the polarization atomic diagnostics have been developed for determining the moments of the electron distribution function,[7] ion drift velocity,[8] and electric field strength in the gas discharge.

The anisotropic processes always occur in plasma,[10] they determine efficiency of pumping of the upper lasing levels, what finally affects the efficiency and energy parameters of lasers. Therefore, an account of the anisotropic collision and radiative processes is needed for solving the problems of kinetics of active media.

An anisotropic character of collisions in a gas discharge plasma is due to the existence of the electronic field causing the drift of charged particles. The effect of the field on collisional and radiative processes is very complicated and it is poorly studied. At the same time electric fields are always observed in plasma (external fields or microfields of the plasma); their strength can reach several hundred kV/cm, and their effect on the atomic state polarization can be significant. Classification of the experimental data based on the polarization degree with the use of theoretical models enables one to reveal some regularities of the radiative and collisional processes that is practically important.

We have studied radiative processes in the electric fields in Refs. 11 and 12. Formulas for the probability of the radiative transitions of atoms in the electric field describing the angular and polarization characteristics of radiation were derived there. The probability of the dipole atomic transition producing photons within a unit solid angle with the polarization being parallel (perpendicular) to the field is given by the formulas

$$\frac{dW_{\parallel}}{d\Omega} = \frac{3}{8\pi} W \left[\beta_{\parallel} \sin^2\theta + \beta_{\perp} \cos^2\theta\right] , \qquad (1)$$

$$\frac{dW_{\perp}}{d\Omega} = \frac{3}{8\pi} W \beta_{\perp} , \qquad (2)$$

where W is the integral probability of the transition, $\beta_{\parallel}$ and $\beta_{\perp}$ are called the coefficients of anisotropy of radiation polarized parallel and perpendicular with respect to the field, respectively. For an isolated atom $\beta_{\parallel} = \beta_{\perp} = 1/3$. In the electric field the coefficients of the anisotropy depend on the field strength and, according to the definition, $0 \le \beta_{\parallel} \le 1$ and $0 \le \beta_{\perp} \le 0.5$. According to the selection rules for the magnetic quantum number M, $\beta_{\parallel} = 0$, when $\Delta M = \pm 1$ and $\beta_{\perp} = 0$, when $\Delta M = 0$.

Maximum emission of atoms will occur in two directions: $\Theta = 0$ and $\pi/2$. When $\beta_{\perp} > \beta_{\parallel}$ the maximum of atomic emission occurs in the direction $\Theta = 0$, and *vice versa*. In the limiting cases ($\beta_{\perp} = 0$ and $\beta_{\parallel} = 1$, or $\beta_{\perp} = 0.5$ and $\beta_{\parallel} = 0$) the anisotropy of emission will be maximum.

Coefficients of anisotropy are independent of the sign M and thus the field effect on the emission is analogous to that of alignment of atomic states.

The angular distribution of the transition probability in general case is much more complicated than in the dipole approximation. This results from the interference of multipole atomic transitions. The primary contribution

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which vanishes with the field fall off comes from the interference of electric dipole and quadrupole transitions. As shown in Ref. 12, this contribution reaches several tens of percents for transition forbidden by the parity condition.

Since, polarization spectroscopy is based on the analysis of spectral line intensities, the interpretation of experimental results should take into account the processes forming the population of upper levels. Formulas (1) and (2) were derived based on the assumption that the population of Stark states is uniform. The anisotropic processes make the analysis of the experimental data much more difficult because the electric field changes the mechanism of collisional population of atomic states.

In Refs. 13 and 14 we have studied the effect of the electric field on the cross section of inelastic electron–atom processes. In the case of high velocity of a bombarding electron the differential cross section of atomic excitation is given by the formula

$$\frac{d\sigma_{nm}}{d\Omega} = \frac{\kappa_m}{\kappa_n} |f^{(B)}_{nm}|^2 \left(1 + 2\mathrm{Re}\,\eta_m(F)\right), \tag{3}$$

where $f^{(B)}_{nm}$ is the transition amplitude in the Born approximation.

$$\eta_m(F) = -\frac{\mu}{h} \int \exp[-i(\kappa'_m r)]\, V^*_{mm}(r) \frac{\exp(i\kappa_m r)}{r}\, dr \tag{4}$$

is the factor depending on the field strength F. For the potential of the form

$$V \sim \frac{\exp\left(-\dfrac{|r + \delta r|}{2a_0}\right)}{r},$$

where $\delta r = \alpha F/e$ (α is the atomic polarizability), $\eta \simeq \eta_0 \left(1 + \frac{\alpha F}{e} \cos\Theta_f\right)$. Here η_0 is the factor of the plane wave distortion by the potential of an isolated atom and Θ_f is the scattering angle.

The electron impact is the basic process which makes the population of energy levels in gas discharges and the anisotropy occurring in this process significantly affects the polarization characteristics[15,16] of the emitted radiation whose polarization degree P can reach several tens of percents. The field contribution may be ambiguous here: it may decrease P imitating thus the relaxation effect or increase it imitating the effect of the beam–like properties of the plasma electron component.

As follows from Ref. 16

$$P = P_0 \pm P_f, \tag{5}$$

where P_0 is the polarization degree due to the anisotropy of the collisional processes and P_f describes the field contribution.

$$P_0 = I_0(-1)^{2J} \begin{Bmatrix} J & J & 2 \\ 1 & 1 & J_0 \end{Bmatrix} \left[\frac{3}{\sqrt{30}} \rho_0^{(2)}(J, J) + \right.$$

$$\left. + \frac{1}{2\sqrt{5}} \left(\rho_2^{(2)}(J, J) + \rho_{-2}^{(2)}(J, J) \right) \right] / (I_\parallel + I_\perp), \tag{6}$$

$$P_f = I_0 \sum_\kappa (-1)^{J_0 - J} \sqrt{2\kappa + 1} \sum_{J'M}^{(+)} \rho_0^{(k)}(J, J') \times$$

$$\times 2\,\mathrm{Re}\, C_J'(M) \begin{pmatrix} J' & J & \kappa \\ M & -M & 0 \end{pmatrix} \left(1 - (-1)^{2J+\kappa}\right) \times$$

$$\times \frac{3}{\sqrt{6}} \begin{Bmatrix} J & J & 2 \\ 1 & 1 & J_0 \end{Bmatrix} \begin{pmatrix} J & J & 2 \\ M & -M & 0 \end{pmatrix} / (I_\parallel + I_\perp). \tag{7}$$

Here J and J_0 are the quantum numbers of the total angular momentum of upper and lower levels, $\rho_0^{(\kappa)}(J, J)$ and $\rho_0^{(\kappa)}(J, J')$ are the diagonal and nondiagonal polarization tensors, I_0 is constant, $I_\perp$ and $I_\parallel$ are the intensities of polarized and cross polarized components of radiation, and $C_{J'}(M)$ are the coefficients of an expansion of the wave function of the Stark states over the states of an isolated atom. The positive sign means that the summation is done only over positive values of M.

Formulas (6) and (7) provide the basis for construction of the method for polarization diagnostics of the plasma in the external field. Such a plasma occurs in the layer near cathode in a glow discharge[18] or in volume beam discharges.[19,20]

The mechanism of pumping helium plasma with electrons under the action of an electric field has been studied both theoretically and experimentally, i.e., by comparing the measured degrees of polarization of helium spectral lines with the values calculated by formulas (5)–(7). The plasma was produced in a gas–discharge tube with plane electrodes. The distance d between the electrodes could be varied by moving grid anode. The accelerating pulsed voltage up to $U_0 = 10$ kV or constant voltage up to 1 kV was applied to the electrodes. To improve the beam characteristics, the cathode made of a high–resistance metal ceramic was used, which made it possible to apply large excess voltage to the accelerating gap that does not yet break the homogeneity of glowing over the entire cathode area.

The property of a discharge to generate electron beams depends on the screening effect of the grid anode preventing penetration of ions from the plasma jet into the accelerating gap and on the volume processes in the gap. As is shown in Ref. 21, helium ions have maximum concentration just beyond the anode due to the screening effect of the grid. This diminishes the role of ion bombardment of the cathode in production of secondary electrons.

The screening effect of the grid disappears with increase of the interelectrode gap and the discharge gradually becomes an ordinary glow discharge with the cathode drop region only several tenths of millimeter thick.

To study the electron beam generating properties of plasma using spectral lines of discharge one should choose the transitions whose upper levels are populated with the direct electron hit from the ground state. In addition, a noticeable Stark effect could also be observed at such upper levels. In the case of helium atoms the transitions $1^1S - n^1P$, ($n \geq 4$) meet these requirements. The line ($1^1S - 4^1P$) at $\lambda = 396.4$ nm is the most intense among them.

In the electric field the forbidden transition $4^1P - 2^1P$ (491.0 nm), whose intensity for $F \sim 40$ kV/cm is comparable to that of the line at $\lambda = 396.4$ nm, appears from the level 4^1P.

As follows from theory,[17] radiation intensities $I_\perp$ and $I_\parallel$ for the transition $4^1P - 2^1S$ depend only on the polarization tensors $\rho_0^{(2)}$ and $\rho_0^{(0)}$

$$\gamma = \frac{I_\parallel}{I_\perp} = \frac{\rho_0^{(0)} - 0.64\rho_0^{(2)}}{\rho_0^{(0)} + 0.32\rho_0^{(2)}} , \quad (8)$$

or when we express the polarization tensors in terms of the elements ρ_{00} and ρ_{11} of the density matrix, we obtain

$$\gamma = \frac{1.91 + 1.09\varepsilon}{0.55 + 2.45\varepsilon} , \quad (9)$$

where $\varepsilon = \rho_{11}/\rho_{00}$.

In a similar way we can derive expressions for the polarization degree of spectral lines

$$P_0 = \frac{0.18\,(1 - \varepsilon)}{(1 + 1.45\varepsilon)} , \quad (10)$$

$$P_f = \frac{0.12\zeta^2\,(1.33 - 1.23\varepsilon)}{(1 + 1.45\varepsilon)} , \quad (11)$$

where $\zeta = 0.02F$ (F is measured in kV/cm).

The degree of polarization of spectral line emission due to the forbidden transition $4^1P - 2^1P$ is independent of the field strength and equals

$$P' = \frac{0.3\,(6.3 - \varepsilon)}{1 + 2\varepsilon} . \quad (12)$$

Using measured values of γ, P, and P' we can calculate by formulas (9)–(11) the populations of Stark states for these transitions and distributions of the electric field strength along the discharge gap. Since the contribution of the electric field to polarization is small very strict limitations are imposed on the accuracy of measurements of $I_\perp$ and $I_\parallel$.

From measurements of $I_\perp$ and $I_\parallel$ we have determined the degree of polarization of spectral lines at λ = 396.4 and 468.5 nm in a pulsed discharge (the amplitude of voltage applied to the acceleration gap 1.8 mm long was 3.5 kV and P = 15 Torr) at maximum of the spectral line intensities as functions of distance z from the cathode. The results are presented in Table I.

TABLE I.

λ, nm	P, %			
	z = 0.7 mm	z = 4 mm	z = 10.2 mm	z = 14.2 mm
396.4	12 ± 5	9 ± 3	9 ± 3	8 ± 5
468.5	12 ± 5	7 ± 3	7 ± 3	5 ± 5

As can be seen from the table, the polarization degree for both lines within the acceleration gap is higher than that in the plasma jet. The estimate by formulas (8) and (9) yields $P_f/P_0 = 0.08$ (for U_0 = 3.5 kV), that is qualitatively confirmed by experimental data. The polarization degree for both lines in the jet remains practically unchanged at the distance from the cathode up to z = 14 mm then it starts to decrease, what is indicative of the beam existence in this region. The depth of penetration of the beam can be estimated by the formula $L = Z_n/(\sigma_n N)$ (see Ref. 22), where Z_n is the number of inelastic acts of interactions of electrons with atoms having the concentration N and σ_n is the total interaction cross section. Under these conditions of the discharge the calculated value of L is about several centimeters that well agrees with measurements.

REFERENCES

1. S.A. Kazantsev, et al., Usp. Fiz. Nauk **156**, 3–46 (1988).
2. K. Blum and H. Kleinpoppen, Phys. Rep. **52**, No. 2, 203–226 (1979).
3. N. Mott and G. Messi, *The Theory of Atomic Collisions,* 3rd ed. (Claredon Press, Oxford, 1965).
4. G.V. Scrotskii and T.G. Izyumova, Usp. Fiz. Nauk **73**, No. 3, 423–470 (1961).
5. A.G. Petrashen', V.N. Rebane, and T.K. Rebane, Zh. Eksp. Teor. Fiz. **87,** No. 1, 147–159 (1984).
6. M.I. D'yakonov and V.I. Perel, ibid. **47**, No. 6, 1483–1495 (1964).
7. S.A. Kazantsev, Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 3, 131–133 (1983).
8. S.A. Kazantsev, et al., Opt. Spektrosk. **68**, No. 6, 1260–1264 (1990).
9. A.I. Drachev, et al., Opt. Spektrosk. **70**, No. 2, 277–283 (1991).
10. M.P. Chaika, *Interference of Degenerated Atomic States* (State University Press, Leningrad, 1975), 195 pp.
11. V.P. Demkin, Opt. Spektrosk. **61**, No. 5, 1048–1056 (1986).
12. V.P. Demkin, Opt. Spektrosk. **61**, No. 6, 1167–1174 (1986).
13. V.P. Demkin, Izv. Vyssh. Uchebn. Zaved. SSSR, ser. Fizika, **32**, No. 1, 10–13 (1989).
14. V.P. Demkin, N.L. Kupchinskii, and I.I. Murav'ev, in: *Abstracts of Reports at the Europh. Conf. 23 rd EGAS*, Torun (1991), Vol. 15d, p. 148.
15. I.C. Percival and M.J. Seaton, Phil. Trans. Roy. Soc. **251 A**, No. 1, 113–163 (1958).
16. J.S. Slevin, Rep. Prog. Phys. **47**, No. 3, 461–489 (1984).
17. V.P. Demkin, Opt. Spektrosk. **71**, No. 3, 389–394 (1991).
18. Yu.P. Raizer, *Physics of Gas Discharge* (Nauka, Moscow, 1987), 662 pp.
19. L.P. Babich, T.V. Loiko, and V.A.Tsukerman, Usp. Fiz. Nauk **160**, No. 1, 49–73 (1990).
20. P.A. Bokhan, Zh. Tekh. Fiz. **56**, No. 6, 1230–1236 (1986).
21. V.P. Demkin, N.L. Kupchinskii, and I.I. Murav'ev, Fiz. Plazmy **18**, No. 10, 1352–1357 (1992).
22. P.I. Gudzenko and S.I. Yakovlenko, *Plasma Lasers* (Atomizdat, Moscow, 1978), 256 pp.