THE MECHANISM OF THE OPTICAL BREAKDOWN IN A GAS

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In order to refine the theory of the laser breakdown in a gas, allowance was made for the phenomenon of photoionization of molecules excited by electron impact, which gave better agreement with the experimental data.

ZEL'DOVICH and Raĭzer[1] considered the mechanism of the avalanche ionization of a gas under the action of a pulse of light. A comparison of the calculated results with the experimental data of Meyerand and Haught[2] and of other authors[3,4] showed that this ionization mechanism was the dominant one.

In our opinion, the photoionization of molecules excited by electron impact should not be neglected. The need to allow for this factor is supported by the following considerations. First, when only the avalanche ionization of a gas is allowed for, the threshold ionization power is found to be proportional to the square of the frequency, which does not agree with the experimental data.[5] Secondly, a comparison of the calculated values of the breakdown fields with the experimental data of Zel'dovich and Raĭzer[1] shows that the breakdown fields depart more and more from the experimental values when the gas pressure is increased. True, Zel'dovich and Raĭzer remark that this may be explained by the inhomogeneous distribution of the radiation field in the ionization region. However, we shall show below that this disagreement practically disappears when the photoionization of excited molecules is allowed for.

We shall allow for the photoionization of excited molecules within the framework of the treatment of Zel'dovich and Raĭzer. We shall assume that the electrons having a binding energy $<\hbar\omega$ are knocked out from molecules practically instantaneously by the applied radiation. We shall neglect the ionization involving two or more photons.

If β is that fraction of electron-impact-excited molecules whose binding energy is $<\hbar\omega$, then, making the stated assumptions, we obtain a modified second boundary condition for Eq. (6.1) in [1]:

$$J(0) = J(I_1)(1-\alpha)(1+\beta) + J(I_1)2\alpha = J(I_1)[1+\alpha+\beta(1-\alpha)], \quad (1)$$

where in accordance with our assumptions

$$\beta = N_{\hbar\omega} / N_{\Delta}, \quad (2)$$

and $N_{\hbar\omega}$ and N_{Δ} are the numbers of molecules excited by electron impact to the energies $I_1 - \hbar\omega$ and $I_1 - \Delta = \epsilon_1$ (ϵ_1 is the energy of the first excited level).

If we neglect the energy dependence of the cross section for the impact excitation in the energy range ϵ_1–I_1, then β will obviously be proportional to the fraction of free electrons in the corresponding energy range. Using the condition of intensive "drain" when $\epsilon = I_1$ and bearing in mind the smallness of Δ compared with I_1, we may approximately assume that the density of electrons is $n \approx I_1 - \epsilon$, and hence

$$\beta = \int_{I_1-}^{I_1} n(\varepsilon)\,d\varepsilon \Big/ \int_{\varepsilon_1}^{I_1} n(\varepsilon)\,d\varepsilon \approx (\hbar\omega/\Delta)^2. \quad (3)$$

Thus, under these assumptions, allowance for the photoionization of excited molecules reduces to the replacement, in the appropriate formulas, of the quantity α with the quantity α' in accordance with the formula

$$\alpha' = \alpha + \beta(1-\alpha), \quad (4)$$

where β is defined by Eq. (3).

The values of β for Ar and He, at frequencies corresponding to the fundamental vibration and the second harmonic of a ruby laser, are as follows: for Ar $\beta_1 = 0.175$, $\beta_2 = 0.70$; for He $\beta_1 = 0.14$, $\beta_2 = 0.56$.

P, mm Hg	E_{theor}/E_{exper}		$E^2_{2\omega} / E^2_{\omega}$	
	Ar	He	Ar	He
1500	0.545	0.98	1.78	2.35
10^4	0.69	1.07	1.26	1.58
10^5	0.52	0.89	1.06	1.13

The table lists the results of the calculation of

the threshold values of the field using β for the fundamental frequency. The calculations were not carried out in full again but we used the fact that $E^2_{thresh} \sim \omega^2/\alpha$. Hence, to obtain new values of the quantity E_{theor}/E_{exper}, we used the formula

$$\left(\frac{E_{theor}}{E_{exper}}\right)_{new} \Big/ \left(\frac{E_{theor}}{E_{exper}}\right)_{old} = \left[1+\beta\left(\frac{1}{\alpha}-1\right)\right]^{-1/2}. \quad (5)$$

To determine the frequency dependence of the threshold power, we calculated the ratio of the threshold powers at the frequencies 2ω and ω. Without allowance for the photoionization of excited molecules, this ratio is obviously 4. The calculation was carried out using the formula

$$E_{2\omega}^2/E_{\omega}^2 = 4\left[1+\beta_1\left(\frac{1}{\alpha}-1\right)\right]\Big/\left[1+\beta_2\left(\frac{1}{\alpha}-1\right)\right].$$

The results are given in the table.

It is evident from Eqs. (4) and (5) that the influence of β increases with decreasing α, i.e., as the gas pressure is increased. Moreover, the value of β itself rises with the frequency. Therefore, the photoionization effect may be neglected only at low pressures and frequencies. As is evident from the data listed for Ar and He, even at the lowest pressures and frequencies, the photoionization effect is noticeable; at high pressure and frequencies, it may be very prominent.

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