OPTICAL BREAKDOWN IN A GAS MIXTURE

E. Gernits, R. M. Minikaeva, V. E. Mitsuk, and V. A. Chernikov

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The threshold for optical breakdown at the focus of a laser beam in mercury vapor [1, 2] at pressures on the order of 1 atm or below is on the same order of magnitude as the electric field of the light wave, 10^6–10^7 V/cm. We report here an experimental study which shows that the threshold for optical breakdown may be reduced in mixtures of mercury vapor and helium or neon. In our experiments we used a neodymium-glass laser with Q modulation by means of a rotating prism. The laser pulse is ~65 nsec long, has an energy of 1 J, and has a divergence of ~5′. The laser beam is focused by means of a lens (f = 26 mm) in a glass vacuum chamber containing mercury vapor and helium or neon.

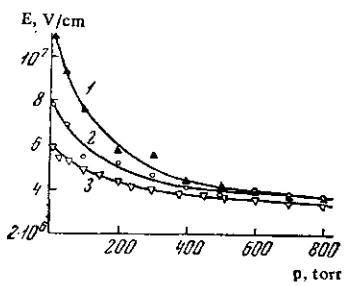

Fig. 1. Threshold electric fields. 1) Impure mercury vapor at pressures up to 800 torr; 2) mixture of mercury vapor and neon at a neon pressure of 400 torr; 3) mixture of mercury vapor and helium with a helium pressure of 400 torr.

To maintain the desired mercury vapor pressure, the chamber is placed in an oven designed to minimize temperature gradients. The chamber is filled beforehand to the desired gas pressure.

Breakdown is detected by a photoelectric method, on the basis of the appearance of mercury spectra lines in the "spark" emission spectrum.

Figure 1 shows threshold electric fields in the light wave as a function of the pressure for breakdown in pure mercury vapor (curve 1) at pressures between 1 and 800 torr; in a mixture of mercury vapor and neon (2), for a neon pressure of 400 torr; and in a mixture mercury vapor and helium (3), for a helium pressure of 400 torr.

Addition of helium or neon to the mercury vapor reduces the breakdown threshold, even though the thresholds for pure helium or pure neon are much higher than the experimental values.

We can explain this effect by assuming that the helium or neon atoms excited into the metastable state transfer energy through collisions to mercury atoms, ionizing them; in addition, collisions of

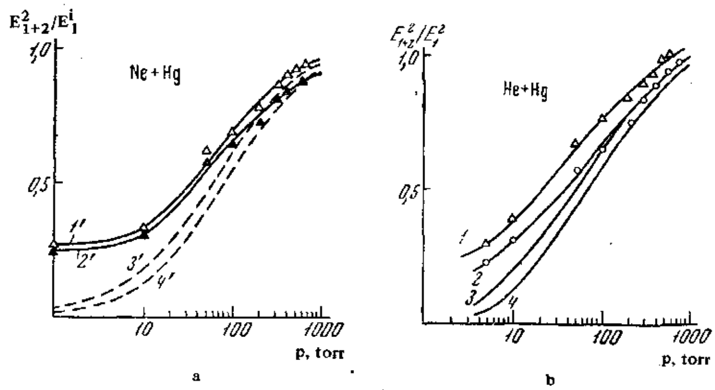

Fig. 2. Field ratio E_{1+2}^2/E_1^2 as a function of the mercury vapor pressure. a: mixture of helium and mercury vapor. 1, 2) Experimental curves at helium pressures of 200 and 400 torr, respectively; 3) theoretical curves for the same pressures. b: Mixture of neon and mercury vapor. 1′, 2′) Experimental curves for neon pressures of 300 and 400 torr, respectively; 3′, 4′) theoretical curves for the same pressures.

a second kind may occur, between electrons and excited helium or neon atoms, as a result of which electrons obtained an energy sufficient to ionize mercury atoms. In either case, excitation of a helium or neon atom ultimately leads to the ionization of the mercury atom. However, estimates made for our experimental conditions show that neither mechanism would result in the reduction of the breakdown threshold observed experimentally.

In a mixture, the rate at which an electron acquires energy due to braking absorption involving neutral atoms, may be greater since the effective collision frequencies, which govern the energy-acquisition rate are added together. Addition of helium or neon to mercury also reduces diffusion loss. Elastic loss should be greater in a mixture, especially since the helium and neon atoms have low masses.

Since the mercury ionization potential($I_i = 10.38$ eV)is less than the energy of the first excited level of helium($I_1^* = 21.1$eV) and of neon($I_1^* = 16.59$eV), an ionization avalanche [3] should develop in such a manner that the mercury is completely ionized first; then the inert gas atoms and ionized only by those electrons having energies above I_i of mercury, of which there are relatively few. When the mercury is completely ionized, braking absorption in Coulomb collisions become predominant, and plasma heating and ionization of the mixture proceed rapidly; i.e., there is a breakdown of the mixture.

According to [4] the breakdown condition for pure mercury

$$\frac{1}{\theta_{cr}} = \frac{\alpha_1 e^2 E_1^2 \nu_{f1}}{m\omega^2 I_1} - \frac{2m\alpha_1 \bar{\varepsilon}}{M_1 I_1}\nu_{f1} - \frac{1}{\tau_D} \tag{1}$$

while that for the mixture is

$$\frac{1}{\theta_{cr}} = \frac{\alpha_{1+2} e^2 E_{1+2}^2 (\nu_{f1} + \nu_{f2})}{m\omega^2 I_1} - \frac{2m\bar{\varepsilon}\alpha_{1+2}}{I_1}\left(\frac{\nu_{f1}}{M_1} + \frac{\nu_{f2}}{M_2}\right) - \frac{1}{\tau D_1 + \tau D_2},$$

where the time constant θ_{cr} for the avalanche development is found from $\theta_{cr} = \frac{\tau}{\ln n/n_0}$ (n/n_0 is the ratio of the final electron density in the focusing region, i.e., that corresponding to complete ionization, and the initial density), α is the probability that an electron will "junk" the excitation-loss zone, I_i is mercury ionization, τ_D is the diffusive lifetime for free-diffusion conditions, ν_f is the effective collision frequency and M is the mass of the corresponding gas component.

From the condition for gas breakdown at the focus of the laser beam, we find the ratio threshold fields for pure mercury vapor and for the mixture to be

$$\frac{E_{1+2}^2}{E_1^2} = \frac{\alpha_1 \nu_{f1}}{\alpha_{1+2}\nu_{f1+2}} \frac{\left(\frac{1}{\theta_{cr}} + \frac{1}{\tau_{D_1} + \tau_{D_2}}\right)}{\left(\frac{1}{\theta_{cr}} + \frac{1}{\tau_{D_1}}\right)}, \tag{2}$$

where E_{1+2} is the threshold field in the gas mixture and E_1 is that in the pure gas.

With elastic losses neglected, the field ratio is independent of α:

$$\frac{E_{1+2}^2}{E_1^2} = \frac{1}{1 + \frac{\nu_{f2}}{\nu_{f1}}}\left[1 - \frac{\frac{1}{\tau_{D_1}}\left(\frac{\nu_{f2}/\nu_{f1}}{1 + \nu_{f2}/\nu_{f1}}\right)}{\frac{1}{\theta_{cr}} + \frac{1}{\tau_{D_1}}}\right]. \tag{3}$$

It is evident from Eq. (3) that both factors on the right side are always greater than unity. The first reflects the decrease in the threshold field due to the increase in the electron-heating rate in the mixture: the second reflects the decrease of the threshold due to the reduction of electron diffusion.

Account of elastic losses, which can always be important at high pressures, especially in light gases, results in

$$\frac{E_{1+2}^2}{E_1^2} = \frac{\alpha_1 \nu_{f1}}{\alpha_{1+2}\nu_{f1+2}} \frac{\left[\frac{2m\bar{\varepsilon}\alpha_{1+2}}{I_1}\left(\frac{\nu_{f1}}{M_1} + \frac{\nu_{f2}}{M_2}\right) + \left(\frac{1}{\theta_{cr}} + \frac{1}{\tau_{D_1} + \tau_{D_2}}\right)\right]}{\left[\frac{2m\bar{\varepsilon}\alpha_1}{I_1}\frac{\nu_{f1}}{M_1} + \left(\frac{1}{\theta_{cr}} + \frac{1}{\tau_{D_1}}\right)\right]}. \tag{4}$$

Figure 2 shows the field ratio E_{1+2}^2/E_1^2 as a function of the mercury vapor pressure.

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Department of Electronics