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EXPERIMENTAL EVIDENCE OF INVERSE BREMSSTRAHLUNG AND ELECTRON-IMPACT IONIZATION IN LOW-PRESSURE ARGON IONIZED BY A GIANT-PULSE LASER*

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The generation of plasma in different gases by a giant-pulse ruby-laser beam has been reported by several authors.[1-3] Mechanisms responsible for the ionization of the gas have also been advanced. The extension of classical microwave breakdown theory[4] has been used to explain the phenomena by Minck.[3] Multiphoton ionization theory has been proposed by Gold and Bebb.[5,6] Keldysh[7] has mentioned the tunnel autoionization mechanism in his paper. The inverse bremsstrahlung process has been suggested by Meyerand and Haught,[1] Wright,[8] and Tomlinson.[9] In this Letter experimental evidence is presented which shows that at low pressures (less than one atmosphere) most of the electrons are produced after the cessation of the laser pulse, and the ionization rise time is increased as the pressure of the gas is decreased. It is also shown that the most probable mechanism for electron production is due to inverse bremsstrahlung and subsequent electron-impact ionization.

The experimental apparatus is shown in Fig. 1. A Q-switched giant-pulse ruby laser (6943 Å) capable of delivering up to 100 MW is focused at a focal point by a lens in an argon atmosphere of pressure from a few millimeters of mercury up to one atmosphere. The gas breakdown at the focal point is observed by an electrostatic probe (two 0.020-in. tungsten wires 0.4 mm apart) to detect the existence of the charged particles. The rise time of the probe circuit and the readout device (Tektonix 519) is less than 1 nsec.

A flow is produced in the test section by letting both the inlet and outlet valves open. The velocity of the drop is obtained by measuring the time of arrival of the drop at a known distance from the focal point. The diameter of the drop (assumed to be spherical in shape) is determined by knowing the velocity of the drop and the temporal width of the electrostatic probe signal registered on the oscilloscope trace. The diameter (defined by distance between points of 10% maximum signals) of the drop as a function of time is obtained by measuring the drop diameter at various times of arrival from the laser focal point with different flow velocities. After cessation of the laser pulse, the main mechanism responsible

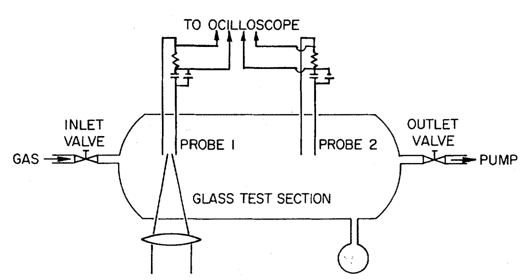

FIG. 1. Schematic diagram for laser breakdown study.

for the expansion of the drop is diffusion.[10,11] Since the electron temperature is much higher than the ion or atom temperature and $m_a \nu_{ia} \gg m_e \nu_{ea}$, the electron temperature or energy can be related to the radius of the drop r and time t from the ambipolar diffusion relation[12]

$$n_e V = D\nabla n_e = (KT_e/m_a \nu_a)\nabla n_e.$$

By using the diffusion length for a sphere (r/π), the last expression can be written as

$$kT_e = \frac{r}{\pi} m_a \nu_{ia} \frac{dr}{dt},$$

where ν_{ia} is the ion-atom collision frequency[13] equal to $1.40\times10^{-14} n_a[8kT_a/\pi m_a]^{1/2}$ with T_a equal to atom or ion temperature (300°K); D the ambipolar diffusion coefficient, V the particle velocity; m_a the mass of atom, n_a the atom density, and ν_{ea} the electron-atom collision frequency. The electron temperature as a function of time is thus obtained.

Both the inlet and outlet valves in the test section are then closed. The current from the probe as a function of time with a known impressed voltage at different gas pressures is obtained when the gas in the test section is in the stagnant condition. The conductivity of the plasma is calculated from the probe current and the volume of the conducting gas which is determined from the size of the plasma drop and the distance between the diameters of the two probe wires (neglecting the sheath thickness). The electron density n_e is related to the conductivity σ by using the expression

$$\sigma = n_e e^2/(q_{ea} n_a + q_{ei} n_e)\bar{c}_e m_e, \qquad (2)$$

where q_{ea} and q_{ei} are, respectively, the electron-atom and the electron-ion elastic-collision cross sections, and $\bar{c}_e$ the electron thermal speed, e the electronic charge, and n_a the atom number density. At an electron temperature of $T_e \sim 10^5$ °K, $q_{ei}n_e \leq q_{ea}n_a$ when $n_e/n_a \leq 0.1$. Therefore, in almost the whole range of the ionization process, the conductivity is dominated by electron-atom collisions and σ is proportional to n_e. Utilizing Eq. (2) with appropriate values q_{ea},[14] neglecting q_{ei}, and using values of T_e obtained from the drop-size measurements described above, n_e normalized to its maximum n_{em} is obtained as shown in Fig. 2.

It is readily seen that at lower gas pressures, most of the charged particles are produced after the cessation of the laser pulse, which is about 18 nsec and is measured in every shot to ensure that there are no multiple pulses. At pressures higher than one atmosphere the ionization time is of the order of, or less than, the laser-pulse time. Thus, the dependency of the ionization time on the pressure cannot be clearly delineated in previous experimental work conducted at high pressures.

The time τ required for an electron to break through the atomic potential barrier can be estimated as follows. The equivalent barrier width is

$$l = I/eF.$$

The average electron velocity is

$$u = (2I/m_e)^{1/2},$$

whence

$$\tau = \frac{l}{u} = \frac{(Im_e)^{1/2}}{\sqrt{2}eF} \sim 5\times10^{-14} \text{ sec},$$

where I is the ionization potential (15.7 eV), e the electronic charge (esu), and F the electric field strength of the laser equal to 2.7×10^6 V/cm. This time interval cannot account for the lag of production of charged particles behind the laser pulse at low pressure. Therefore, the possibility of multiphoton absorption[5,6] and tunnel autoionization[7] as a main mechanism responsible for the production of the charged particles by the laser beam can be excluded.

An estimation of the ionization has also been made based upon the assumption that some preexisting electrons gain energy from the laser

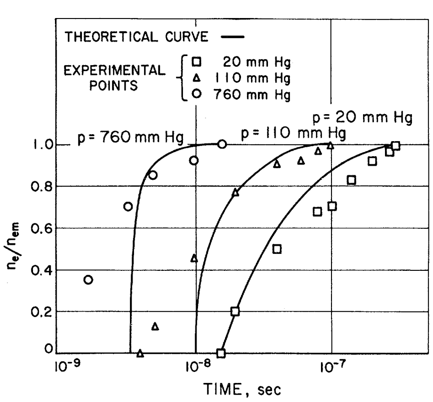

FIG. 2. Electron density as function of time.

radiation through the inverse bremsstrahlung processes and ionize the gas by excitational collisions with the gas atoms as described in Phelps's work.[15] By using the concept of the mutual absorption coefficient for the photon-electron interaction given by Wheeler and Wildt[16] and the elastic and excitational collision cross section given by Massey and Burhop,[17] and assuming the rate of ionization to be limited by the rate of excitation to the first excited state, the electron density has been computed for the conditions shown in Fig. 2. The results (solid lines, Fig. 2) are in qualitative agreement with the experimental data and show similar pressure dependence. The possibility of production of a small amount of high-energy electrons by photon ionization which ionize the gas by impact without the inverse bremsstrahlung process can also be excluded by cross-section considerations.[9]

It is therefore concluded that the ionization process in the argon gas irradiated by a laser beam is inverse bremsstrahlung and electron inelastic collisions. The evidence supporting the electron impact process in high-pressure gases has recently been published.[18]

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ELECTRON-HYDROGEN IONIZATION: THE ASYMPTOTIC FORM OF THE WAVE FUNCTION AND THE THRESHOLD BEHAVIOR OF THE CROSS SECTION

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The problem of the ionization of atomic hydrogen by electron impact is a fundamental problem involving the wave function of three separated charged particles. In addition to its theoretical interest, the problem is of considerable current importance because recent observations of the elastic resonances in electron-hydrogen scattering[1] are limited in accuracy as a result of the theoretical uncertainty of the true shape of the ionization cross section, whose starting point is a key reference point in determining the experimental energy scale.

Although there have been numerous approximate calculations of the ionization cross section of atomic hydrogen by electron impact, it is only comparatively recently that attempts have been made to put this problem on a more