$V(r)\simeq v(r)$; further, we find that we can expand $v(|\mathbf{r}-\boldsymbol{\rho}+\mathbf{R}|)$ in powers of r and ρ and retain only quadratic terms. The contribution to $w(r)$ from this region is

$$B(R)\left[r^2-\omega^{-1}\int_0^\infty dr\, r^2u^2(r)\right], \tag{A6}$$

where

$$B(R)=4\epsilon\sigma^{-2}[22C_{14}(\sigma/R)^{14}-5C_8(\sigma/R)^8], \tag{A7}$$

and

$$C_m=\sum_{\beta=11}^{\infty} n_\beta(R/R_\beta)^m. \tag{A8}$$

Our numerical procedures were sufficiently accurate to give three-place accuracy in E_0 in each iteration. A sufficient number of iterations were run so that E_0 was determined numerically to 1%.

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Laser-Induced Prebreakdown and Breakdown Phenomena Observed in Cloud Chamber*

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Direct observation of initiating electrons below the threshold for visible breakdown discharge is reported. With the cloud-chamber techniques used, minimum detectable ionization is estimated at 5000 ion pairs/cm³. Production of initial electrons is ascribed to photoionization, in a manner which is consistent with Phelp's model. Above the visible breakdown threshold, thermal-gradient effects overcome all other sources of droplet formation in the cloud chamber.

In this article the observation of laser-induced prebreakdown ionization[1,2] and breakdown phenomena[3–19] in a continuously sensitive cloud chamber[20–22] is reported. The nature of the cloud chamber is such that two separate and easily distinguishable effects are produced when the laser power is above and just below the breakdown threshold.

This observation of prebreakdown ionization is the first direct evidence that the breakdown-initiating electron is produced by ionization of vapor by the laser beam. Additionally, it contradicts the assumption[1,4,5,9] that if an initiating electron is present, breakdown is inevitably produced by an avalanche process. The fact that breakdown can be realized in the cloud chamber is indirect evidence that the trigger electron is not naturally present.[1,18] The specific form of the breakdown phenomena also gives indirect evidence of multimode laser characteristics.[23]

The laser system incorporated a $\frac{1}{4}$-in. diameter 3-in.-long ruby rod pumped by an E. G. & G. FX67B lamp. The Q-switched laser pulse had a peak power of approximately 10 MW, i.e., 0.2 J of optical energy was emitted in 30 nsec. Standard techniques for the operation of a continuously sensitive cloud chamber were used.[20,21] A 100-V/cm clearing field was applied. The condensable material was methanol or dimethyl methylphosphonate (DMMP).

Prebreakdown ionization was observed when the laser beam was focused into the sensitive volume of the cloud chamber. Clusters of droplets ranging in diameter from 0.1 to 0.5 cm formed and fell to the bottom of the chamber at about the same rate as the background mist.

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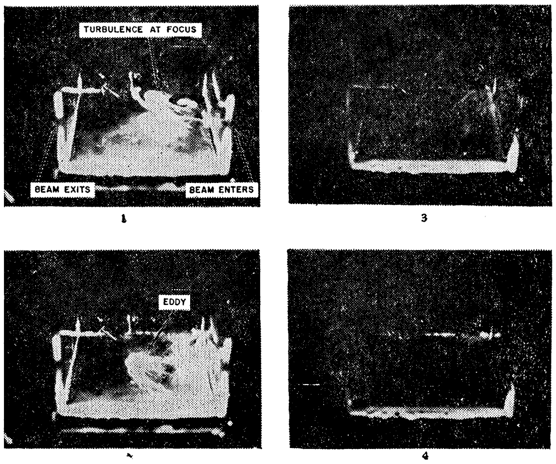

FIG. 1. Sequential photographs of clouds formed in DMMP-air cloud chamber after breakdown.

These droplets were observed at the beam focus when the laser power was below the breakdown threshold.

The droplets are attributed to nucleation on charge particles produced by ionization of vapor by the laser for the following reasons. Ionization of dust[1] or nucleation on dust is ruled out since its presence is effectively removed by cloud chamber operation. The cloud chamber is sensitive to cosmic-ray tracks which produce minimum ionization of about 5000 ion pairs/cm^3 at the site of a track,[22] and this is easily seen by the eye. The local ionization level produced by cosmic-ray background in a small volume, say 1 mm^3, fluctuates considerably. No tracks were observed passing through the focal volume when prebreakdown ionization was observed there. Also, naturally occurring electrons from other parts of the chamber would be swept away by the electric clearing field. Therefore, the background ionization level at the focal volume was far below the average value, 20 ion pairs/cm^3 sec; that is, prebreakdown ionization could not have been triggered by an electron produced by a cosmic ray.

Evidence has also been found by others[1,7,12,16,17] which indicates that the trigger electron is probably not due to natural causes. For example, the time of breakdown appears to be constant.[12,16,17] Also, the presence of electric and magnetic fields[1,7,17] and external ionization sources[1,18] do not measurably affect breakdown characteristics. The origin of the initial electron is unresolved, but many[5,6,11,15,17,19] feel that it may be produced by multiphoton ionization directly by the laser beam. Our experiments ascribe the initial electron directly to the laser beam, but do not specify the mechanism.

Electron probe techniques have been used previously by Tomlinson[1,2] in several attempts to detect laser induced prebreakdown gas ionization in air. Early measurements[2] in some cases indicated the presence of a total of approximately 10^7 "prebreakdown" photo-ions. Recent experiments[1] fail to confirm the earlier observations despite the fact that a much more intense laser beam was used. A typical value which the electron probe technique is capable of measuring is 10^{11} electrons per cm^3. By contrast the cloud chamber, with a resolution of 5000 ion pairs/cm^3, is considerably more sensitive than the electron probe.

Phelps[11,17] has proposed the following idealized model for breakdown by an avalanche ionization process. It is assumed that the initiating electron is easily produced directly by the nonlinear process and that some of the collisionally excited atoms and molecules are immediately photoionized. The electron density, then, increases exponentially due to free-free photon absorption by electron-neutral collisions. When the gas is about 0.1% ionized, the electron density increases rapidly due to larger cross section for free-free photon absorption by electron-ion collisions until the gas is completely ionized. That is, once the gas is 0.1% ionized, breakdown inevitably follows. The 5000 ion pairs/cm^3 is considerably less than 0.1% of the vapor molecules in a cubic centimeter. Therefore, it appears that our observation of prebreakdown ionization *without breakdown* occurs during the period when the electron density is increasing exponentially. When breakdown does not follow, it appears that a combination of laser power characteristics and radial diffusion losses at atmospheric pressure prevents the electron density from growing to 0.1% ionization withing the 30-nsec laser pulse.

When the threshold for breakdown was exceeded, a bluish plasma was formed at the focus. Profuse swirling

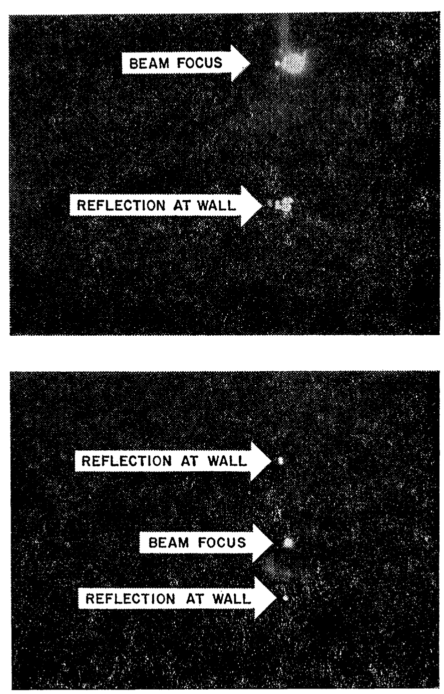

FIG. 2. Photographs of breakdown in cloud chamber illuminated by plasma radiation.

clouds originate at the focus and expand to a diameter of about 2 in. in a few seconds, providing a simple method for distinguishing between breakdown and prebreakdown ionization. Sequential photographs were taken of these clouds within a few minutes after breakdown occurred, and they are shown in Fig. 1. This breakdown followed by cloud effects was observed throughout the cloud chamber independent of the ion-sensitive region. The clouds also completely overshadowed any condensation due to ionization.

Photographs of breakdown illuminated by the plasma radiation were obtained as shown in Fig. 2. In this figure several plasma spots appear to be produced near the focus of the lens. The number of spots varied from one to three on successive laser shots. This can be ascribed to multimode oscillation of the ruby rod, a subject of current controversy.[23] The spectrum of these plasmas included a continuum with peak optical intensity in the blue region, as observed through a diffraction grating.

Our interpretation of the breakdown phenomena observed in the cloud chamber agrees with that of Haught.[8] Following laser breakdown, about half of the laser energy is absorbed into a focal volume of about one cubic millimeter. Heat diffuses outward from the focus and upsets the normal equilibrium conditions in the chamber. Condensation is produced in the form of visible clouds which do not resemble droplets nucleated by charged particles. The clouds were, therefore, interpreted as precipitation of supersaturated vapors due to high local-temperature gradients produced by the breakdown phenomena.

Experiments are in progress to measure the prebreakdown ionization quantitatively as a function of laser power and time to determine if the electron density increases exponentially in this region as Phelps predicts.

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Stark Broadening of an Ionized-Mercury Line

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The profile of the line Hg II λ3984 emitted from a high-current mercury arc of mean temperature 6500 ±800 °K and with electron density $(2.6\pm0.7)\times10^{16}$/cc was studied with a Fabry-Perot etalon. The full half-width of a single even-isotope component due to Stark broadening was found to be 0.39 ± 0.08 cm^{-1}, in which the broadening due to the Doppler effect is subtracted, and the shift relative to an unperturbed line was found to be -0.013 ± 0.010 cm^{-1}. The shift can be interpreted to be due to distant collisions of the perturbing electrons; approximately 90% of the width was found to be due to close collisions.

A HIGH-current mercury arc within a quartz tube of vertical type fed by 200 V ac was viewed in the horizontal direction and was studied spectroscopically. The temperature was determined by the method described by Göing,[1] and the mean temperature of the luminous part was found to be 6500±800°K, from which the mean velocity of the plasma electrons is calculated to be $\langle v\rangle=4.4\times10^{7}$ cm/sec. The mean electron density was obtained by observing the series $6^3P_1-n^3D$; the line λ2352 ($n=10$, $n^*=6.95$) was still recognized as a line, but the next member ($n=11$, $n^*=7.95$) was found to form a continuous band with higher members. Since Inglis-Teller's formula

$$\log_{10}N=23.26-7.5\log_{10}n_m$$

is based on hydrogen wave functions, one puts n_m^* (instead of n_m)[2] in this formula, namely

$$n_m^*=(6.95+7.95)/2=7.45.$$

In this way one gets $N=5.2\times10^{16}$, and assuming that $N_e=N_i$ one obtains $N_e=2.6\times10^{16}$. This is probably accurate to ±30%.

The profile of the ion line Hg II λ3984 (classified by Paschen[3] as $5d^96s^2\,{}^2D_{5/2}-5d^{10}6p^2P_{3/2}$) was studied with a Fabry-Perot etalon with a spacer in the range 1.0–2.0 mm. The same line emitted from a liquid-air-cooled hollow-cathode discharge tube was chosen as an unperturbed standard.[4] The line λ3984 has a hyperfine

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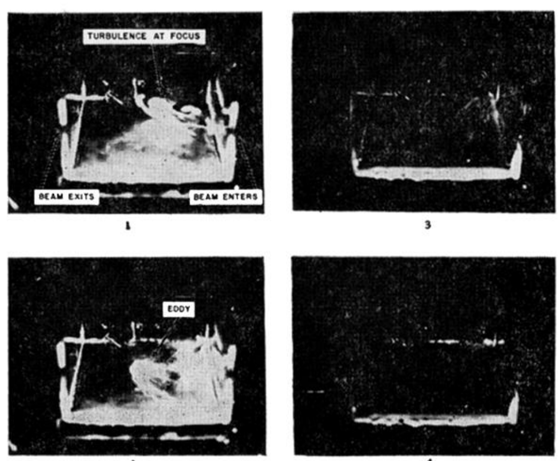

FIG. 1. Sequential photographs of clouds formed in DMMP-air cloud chamber after breakdown.

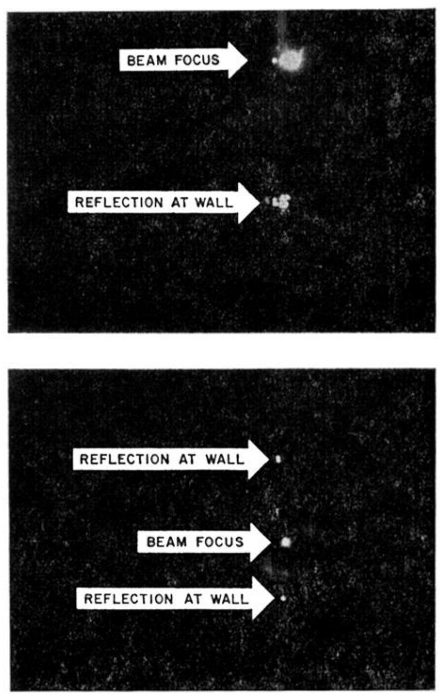

FIG. 2. Photographs of breakdown in cloud chamber illuminated by plasma radiation.