The ionization trace rises sharply in less than 20 nsec, then decays in several hundred nanoseconds.

The minima in the breakdown curves are predicted by the familiar theory of electron impact ionization. The change in energy of the electrons is given by $d\epsilon/dt = e^2E_0{}^2\nu_m/2m \times(\nu_m{}^2+\omega^2)$, where E_0 and ω are the amplitude and frequency of the light wave, ν_m is the electron momentum-transfer collision frequency with neutrals, and e and m are the charge and mass of the electron. This energy change has a maximum when $\nu_m=\omega$. The collision frequency ν_m is related to pressure p (mm Hg) by

$$\nu_m = p_0 P_c v = (5.4\times10^7)P_c U^{1/2}p, \qquad (1)$$

where $p_0=(273/T)p$ is the reduced pressure, P_c is the collision probability, v is the velocity, and U is the mean energy in electron volts. The approximate range of energy U is from the thermal energy, 0.04 eV, to the ionization potential, 24.5 eV for He, 15.7 eV for Ar, and 15.5 eV for N_2. Data are readily available from the literature giving P_c in terms of $U^{1/2}$ for most gases. For He the product $U^{1/2}P_c$ changes very little for U between 4 and 25 eV. Using a value in this range and setting $\nu_m=\omega=2.72\times10^{15}$ $\sec^{-1}$ in Eq. (1) gives $p=21\,400$ psi for the pressure at which the minimum in the breakdown curve should occur. The same procedure for Ar predicts the minimum to be at $p=3300$ psi. These results are in agreement with the experimental data presented, being quite close for Ar and within a factor of 2 for He. In N_2 interpretation of the results must take into account the low-level inelastic collisional processes prevailing as well as the elastic.

It should be noted that the curve of P_c vs $U^{1/2}$ for He has a very broad maximum. The minimum in the curve of threshold E versus pressure is correspondingly broad. For Ar and N_2 the P_c maxima are much sharper, and correspondingly so are the threshold minima.

In conclusion, minimum breakdown fields have been observed for laser-induced discharges. These minima are characteristic of electron-impact ionization where electron heating occurs through energy transfer from the light wave to the electrons undergoing collisions with neutrals. The presence, pressure, and sharpness of these minima are predicted by a simple electron-impact ionization theory, and these predictions agree with the experimental data presented here.

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FREQUENCY DEPENDENCE OF OPTICALLY INDUCED GAS BREAKDOWN*

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The frequency dependence of the threshold intensities for the breakdown of gases by optical maser radiation has been of interest in attempting to determine the fundamental energy coupling mechanisms responsible for the breakdown phenomenon. Investigations by the authors[1] using 1.06μ radiation from a Nd-in-glass and 0.69μ radiation from a ruby optical maser led to the conclusion that the threshold intensity for breakdown increases with decreasing wavelength. A similar observation was made by Haught, Meyerand, and Smith in He, Ar, and air[2] at the same maser frequencies, and by Akhmanov et al.[3] using the Nd radiation and its second harmonic in air. We have made further studies of breakdown thresholds in research grade Xe and Ar at four optical wavelengths and have concluded that the thresholds do not increase monotonically as the wavelength is decreased.

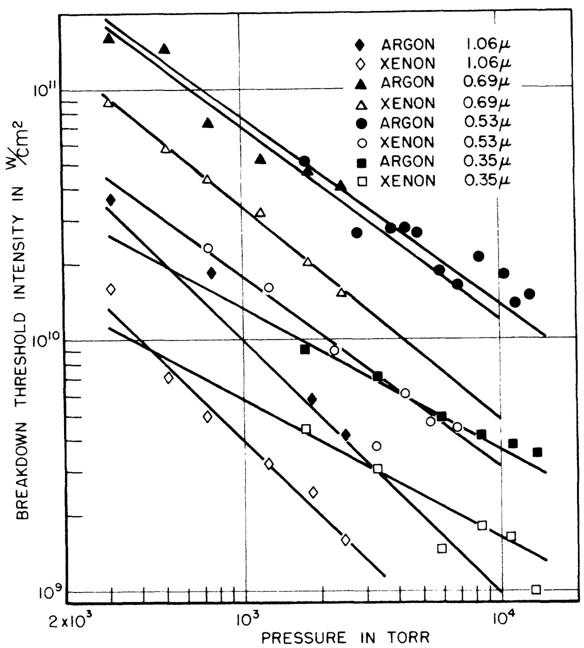

FIG. 1. Breakdown threshold intensity versus gas pressure at four wavelengths.

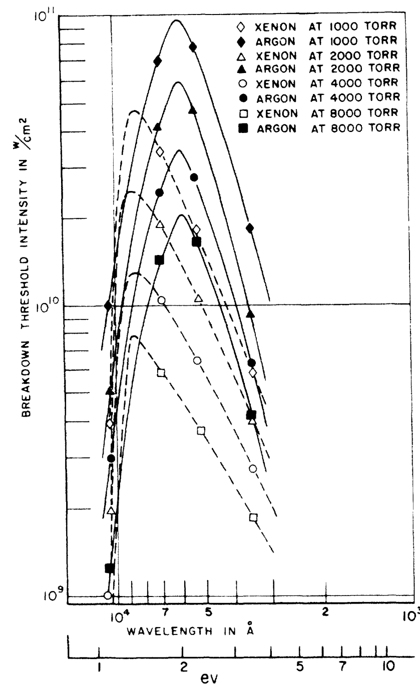

FIG. 2. Breakdown threshold intensity versus wavelength of input radiation at four selected pressures.

The four wavelengths used were the Nd and ruby optical-maser fundamentals and their second harmonics, i.e., 1.06, 0.69, 0.53, and 0.35 μ. The thresholds as a function of pressure in Xe and Ar are shown in Fig. 1. The 1.06 and 0.69μ radiation was focused by a 55-mm focal length lens, and the second-harmonic radiation was focused by an 18.4-mm focal length lens. The cross-sectional areas of the focused spots (listed in Table I) were measured by photographing the focal region directly with the input beam attenuated well below breakdown threshold as in earlier work.[4] The threshold intensity was taken as the peak intensity of the smallest input pulse that would cause visible breakdown. At all four wavelengths, the thresholds exhibited the type of pressure[5] and temporal dependence[4] associated with a cascade growth of the breakdown plasma.

Figure 2 shows threshold intensity in Xe and Ar as a function of optical-maser wavelength. It is clear from Fig. 2 how, based on the earlier two-frequency data,[1-3] the conclusion could be drawn that the threshold increases monotonically with decreasing wavelength. While there is no existing theory to explain

Table I. Input pulse width, focused spot cross-sectional area, and threshold intensity at a fixed pressure for five of the noble gases.

Gas	Threshold intensities at pressure of 2000 Torr (10^{10} W/cm^2) $\lambda = 10\,600$ Å	$\lambda = 6943$ Å	$\lambda = 5300$ Å	$\lambda = 3471$ Å	Ionization potential (eV)
Xe	0.2	1.9	1.06	0.4	12.13
Kr	0.39	3.3			13.99
A	0.51	4.1	4.7	0.91	15.76
He	1.4	7.6			24.58
Ne	2.0	10.0			21.56
3-dB pulse width (nsec)	40	40	28	20	
Spot area (μ^2)	3480	1050	827	185	

the data shown in Fig. 2, it is well known that for gas breakdown induced by classical microwave fields, the threshold intensity does increase with the square of the frequency (assuming that the frequency is much greater than the electron collision frequency), and it is expected that this classical behavior will no longer be observed as the input photon energy approaches the excitation energy of the gas.

Table I gives threshold intensities at a pressure of 2000 Torr. From the Nd and ruby maser data for the five noble gases, we see that the thresholds are inversely related to ionization potential, except for He and Ne. This is not surprising if the breakdown results from a cascade growth process, since for low electron energies, the electron-atom collision cross section is higher for He than for Ne.[6]

As indicated in Table I, the input pulse durations and focused spot sizes were not identical at each wavelength. It has been observed that the threshold intensities decrease with increasing pulse duration and focal volume. The focal-volume dependence apparently arises from a diffusionlike loss mechanism.[2] Nevertheless, if the data in Fig. 2 were adjusted by redefining the threshold intensity as the average intensity over the duration of the threshold pulse, and adding an empirical correction for the focal-volume dependence, the conclusions of this Letter would remain unchanged. However, the absolute values of the threshold intensities for the 0.53 and 0.35μ radiation would be lower.

Preparatory experiments with the 0.53μ radiation revealed a cloud of bright scattering centers in the beam, which could be seen even with the focusing lens removed. This phenomenon was apparently due to impurities in the gas, and was substantially eliminated by scrupulously drying the breakdown chamber. Although the effect produced negligible attenuation of the input beam, it did tend to raise the breakdown threshold intensity, particularly at high pressures. The greater sensitivity of the eye at 0.53 μ may account for the fact that no such effect was observed at the other three wavelengths.

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DIRECT EXPERIMENTAL TEST OF THE PY AND CHNC INTEGRAL EQUATIONS*

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Of the many existing theories for predicting molecular distribution functions of fluids, two that have gained recent prominence are the Percus-Yevick (PY) approximation[1] and the convoluted hypernetted chain (CHNC) approximation.[2,3] The acceptance which these two approximate theories have achieved is based on the moderately good agreement between predicted thermodynamic properties and experimental values.[4] Most of the methods used to test these theories fall into two groups. In the first group are computations based on relatively simple potential functions, e.g., the hard-sphere model, in which predicted virial coefficients are compared with exact theoretical values,[5,6] or for slightly more complicated potentials, with Monte-Carlo results.[7] In the second grouping, more realistic potentials are used, e.g., the Lennard-Jones 6-12, and the results are tested by comparing predicted distribution functions or thermodynamic properties with available experimental data.[8] As far as a test of the basic PY or CHNC theory is concerned, the first grouping suffers because,