Table II. Effective cross section for production of Xe^{124}, Xe^{126}, and Xe^{128} from spallation of barium by cosmic rays. A cosmic-ray flux of 5 particles per cm^2 per second was assumed in the meteorite.

Meteorite	Effective production cross section (in units of 10^{-24} cm^2)		
	Xe^{124}	Xe^{126}	Xe^{128}
Stannern	0.071	0.124	0.130
Pasamonte	0.058	0.085	0.085
Juvinas	0.097	0.154	0.206
Petersburg	0.102	0.159	0.179
Moore County	0.059	0.103	0.103
Pena Blanca Spring	0.055	0.118	0.051
Average	0.07 ± 0.02	0.12 ± 0.03	0.13 ± 0.06

This one value, 3 ppm[11] for Johnstown, confirms our expectation of a low barium content. We have rather arbitrarily selected a Ba value of 2 ppm to be used for Pena Blanca Spring.

Table II shows the results of these calculations of the "effective production cross sections." Considering the fact that we have chosen meteorites with a wide range of cosmic-ray exposure [$(2.2$ to $46) \times 10^6$ yr], a wide range of barium concentrations (2 to 48 ppm), and a varying amount of "primordial" xenon [$(0.25$ to $1.7) \times 10^{-11}$ cc STP/g], the relatively small variation from the average value of the effective cross sections (0.07 ± 0.02, 0.12 ± 0.03, and 0.13 ± 0.06 barns for Xe^{124}, Xe^{126}, and Xe^{128}, respectively) thus obtained seems to us to be rather firm evidence for the mechanism of cosmic-ray spallation reactions on barium in meteorites during the past few (2 to 50) million years.

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BREAKDOWN MINIMA DUE TO ELECTRON-IMPACT IONIZATION IN SUPER-HIGH-PRESSURE GASES IRRADIATED BY A FOCUSED GIANT-PULSE LASER*

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Minima in the curves of threshold electric field versus pressure for ionization of super-high-pressure helium, argon, and nitrogen using a focused giant-pulse ruby laser are reported here. These minima are characteristic of electron impact ionization. Gold and Bebb[1] and others have analyzed ionization produced by focused lasers in terms of multiphoton absorption alone. Tomlinson[2] has shown that while multiphoton absorption may be the trigger mechanism, it cannot explain the subsequent growth of the ionization. Meyerand and Haught[3] have suggested that the mechanism is inverse bremsstrahlung. Askaryan and Rabinovich[4] have commented on the prospective role of electron impact ionization. This Letter presents definitive experimental data which are indicative of electron impact ionization where the heating of electrons occurs through energy transfer from the light wave to the electrons undergoing collisions with neutrals.

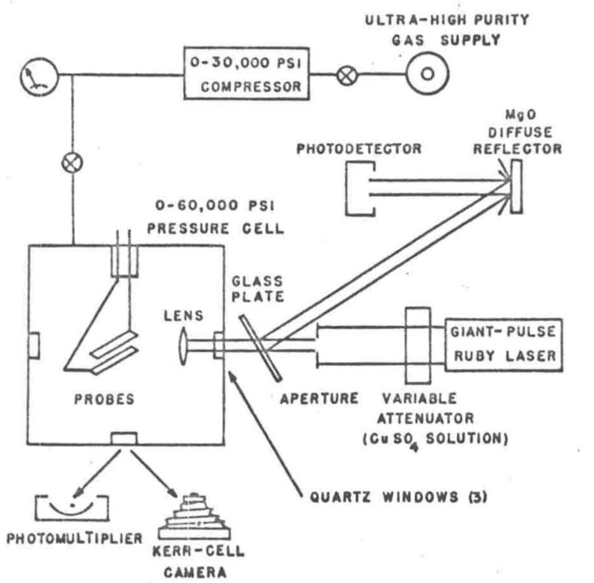

FIG. 1. Experimental apparatus for measurement of gas breakdown at super-high pressures using a focused laser beam.

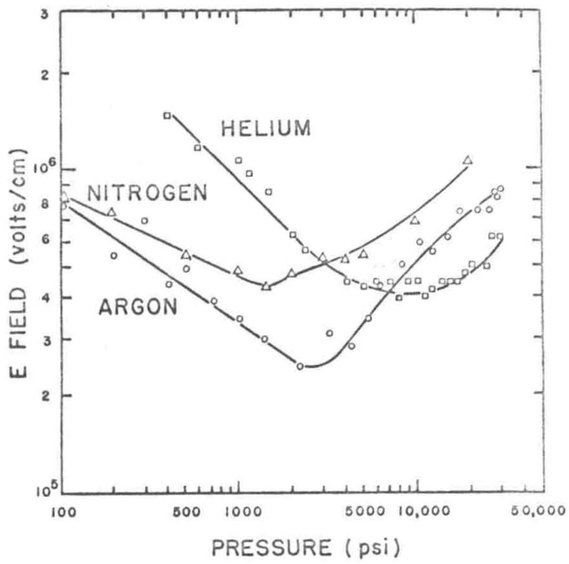

FIG. 2. Pressure dependence of breakdown field strength.

The experimental arrangement is shown in Fig. 1. Breakdown is produced in ultrahigh-purity helium, argon, and nitrogen at pressures up to 30 000 psi by focusing an attenuated 30-MW giant-pulse ruby laser beam within a super-high-pressure cell having three quartz windows. The cell has electrodes on either side of the focal point to sweep out the ionization products. The output pulse of the Kerr cell Q-switched giant-pulse laser has a pulse width at half-amplitude of 50 nsec. The laser beam passes through a $CuSO_4$ solution attenuator, a variable aperture, and a glass plate (microscope slide), and then into the cell where the beam is focused to a point by a 40× microscope objective. The glass plate reflects a small portion of the beam onto a diffuse reflector (MgO block). This monitor beam is then detected by a calibrated fast-rise photodiode. The detector assembly is calibrated prior to the experiment by removing the objective and measuring the intensity of the laser beam passing through the cell. The variable aperture reduces the laser-beam diameter to match the aperture of the objective.

Ionization is detected by a photomultiplier directed perpendicular to the laser-beam path. The input to the photomultiplier is band-block filtered so as to reject the incident and scattered 6943Å ruby laser light. Ionization can also be observed visually or by a Kerr-cell camera system.

Experimental results are shown in Fig. 2. For each pressure the threshold power was determined by successively attenuating consecutive pulses until no ionization occurred. Attenuation was achieved by increasing the density of the $CuSO_4$ solution. Peak electric fields were calculated using the measured power and the minimum focal area determined by burning holes in thin metal foil. The diameter of the minimum focal area was about 100 μ. These conditions give $E=(3.1\times10^3)P^{1/2}$, where E is in V/cm and P in watts.

The curves of threshold peak E field versus pressure in Fig. 2 clearly show minima. In He the minimum is broad and centered about 10 000 psi, with a value of 4×10^5 V/cm. In Ar the minimum is sharper and is centered at 2500 psi with a value of 2.5×10^5 V/cm. In N_2 the curve is also sharp and is centered at 1500 psi with a value of 4.4×10^5 V/cm. No previous work has been reported at pressures above 2000 psi. Below this pressure the He and Ar data presented here agree reasonably well with those of Meyerand and Haught,[3] falling somewhat below their curve (they did not report on N_2). The discrepancy is easily accounted for by the inaccuracy of measurement of the minimum focal area. It is important to note that the slopes of the curves below 2000 psi agree very well with those of reference 3.

The oscilloscope traces showing ionization were similar to those previously reported.

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 $\nu_m = \omega = 2.72 \times 10^{15}$ 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.