We thank K. Fuchel and K. Brightman for their enthusiastic help in adapting the programs for use on the Brookhaven computers. We are indebted to G. H. Vineyard for his helpful comments and particularly for drawing our attention to the similarity between our $\langle r^2\rangle$ curves and his earlier work.

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†This work was performed under the auspices of the U. S. Atomic Energy Commission.

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OBSERVATION OF COOPERATIVE EFFECTS IN THE SCATTERING OF A LASER BEAM FROM A PLASMA

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(Received 3 January 1966)

Incoherent scattering of radiation from a plasma has been treated theoretically by a number of authors.[1] The spectral distribution of the scattered radiation is a function of the parameter

$$\alpha = \lambda_0/4\pi\lambda_D \sin\tfrac{1}{2}\theta, \qquad (1)$$

where λ_0 is the wavelength of the incident radiation, $\lambda_D = (kT_e/4\pi n_e e^2)^{1/2}$ is the Debye length in the plasma, θ the angle of observation of the scattering measured with respect to the forward direction, n_e the electron density, and T_e the electron temperature. For $\alpha \ll 1$, the spectrum reflects the electron velocity distribution and, for a thermal plasma, is a Gaussian centered on the wavelength λ_0. This has been observed by a number of workers.[2-5] For $\alpha \gg 1$, the spectrum is modified by cooperative interactions between the ions and electrons and consists of a central feature, whose width is of the order of the Doppler shift for ion thermal velocities, flanked by a pair of satellites, corresponding to scattering from longitudinal electrostatic oscillations in the plasma, which are displaced from the wavelength of the incident beam by

$$\Delta\lambda = \frac{\omega_p}{2\pi c}\lambda_0^2\left(1+\frac{3}{\alpha^2}\right)^{1/2}, \qquad (2)$$

where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the plasma frequency. The central ion peak has been observed in radar backscatter from the ionosphere.[6] For a thermal plasma only $1/\alpha^2$ of the scattered radiation lies in the satellites and, as a result, these have so far only been observed[7,8] under conditions in which the level of electron density fluctuations is enhanced by nonthermal processes, although observation of the emergence of the satellites under conditions such that $\alpha \sim 1$ has been reported by Kunze, Fünfer, Kronast, and Kegel,[3] by Kunze,[4] and by Ramsden and Davies.[9] Experiments designed to observe cooperative effects in the forward scattering of a ruby-laser beam from a plasma have been reported by DeSilva, Evans, and Forrest[4] and by Bartoli, Katzenstein, and Lovisetto,[10] and evidence has been obtained for a narrow central ion peak when $\alpha > 1$. We have been carrying out a similar experiment and wish to report measurements which show

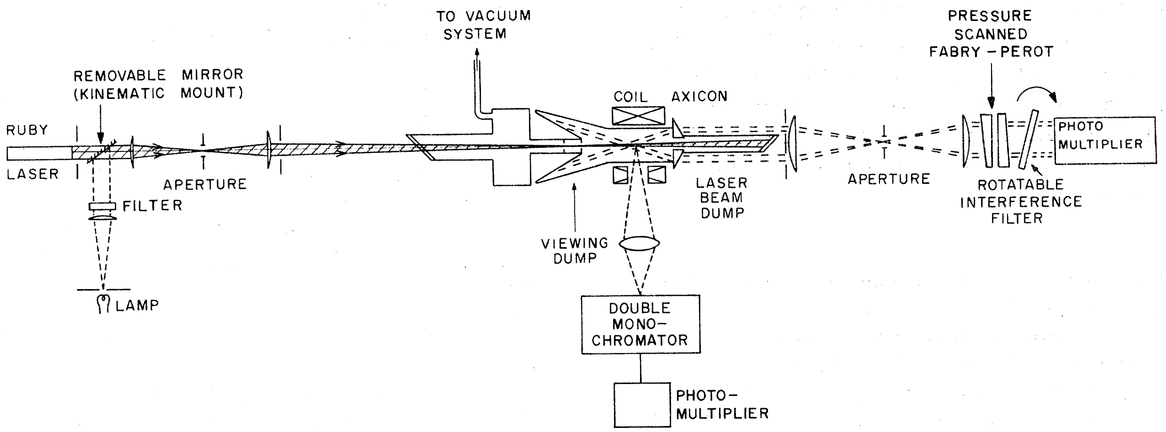

FIG. 1. Experimental arrangement.

both the ion peak and the satellites and which correspond to the results expected for a plasma in which the electrons have a thermal velocity distribution.

The apparatus (Fig. 1) is similar to that used earlier[2] for observations of the Gaussian distribution under conditions such that $\alpha < 1$, with the exception that the scattered radiation is now also observed at an angle of 13.5° to the forward direction. The plasma is produced in a small θ pinch consisting of a 0.55-μF capacitor which is discharged, at 35 kV, into a single-turn coil surrounding a Pyrex tube filled with H_2, at a pressure of ~150 μ Hg. The discharge is triggered from the rotating-prism Q-spoiled ruby laser which has an output power of ~10 MW and a pulse width of ~30 nsec. The laser beam, which is plane polarized and has a divergence of ~2 mrad, is first focused onto a 1-mm aperture by a 50-cm focal-length lens, and then refocused onto two baffles at the entrance to the scattering volume, which serve to reduce stray light seen by the detector. Although not so shown on the diagram, the first lens is slightly inclined to the optic axis, and light reflected from it onto a photodiode is used to monitor the laser beam. A simulated laser beam consisting of a white light source, collimating lens, and red filter is used to align the system.

After passing through the discharge tube, the laser beam is absorbed at the end of a 20-cm-long glass tube by a piece of black glass at the Brewster angle. Radiation scattered in the forward direction is collected over an annular region by means of a quartz conical lens, or axicon, and focused by a plano-convex lens onto an aperture which limits the range of scattering angles accepted to between 13.2° and 13.8°. The discharge tube is provided with a viewing dump which acts as a black background for the direction of observation. The beam dump, discharge tube, and viewing dump are all painted with an index-matched black paint to reduce stray light in the system.

A combination of a 5-Å half-width rotatable interference filter and pressure-scanned Fabry-Perot interferometer with an interorder separation of 12 Å and a half-width of 1 Å is used to determine the spectral distribution of the scattered radiation, the detector being an RCA 7265 photomultiplier.

Measurements have been made in the afterglow, 18.0 ± 0.2 μsec after the beginning of the discharge, when the plasma is reasonably reproducible and may be expected to be thermalized. Approximately 4×10^{-12} of the incident beam is scattered in the forward direction from an element of volume approximately 1 mm in diameter and 2 cm long at the center of the discharge tube. The spectral distribution of the scattered radiation is shown in Fig. 2(a). The data, taken on successive discharges, show considerable scatter, which is probably due to slight variations in plasma conditions and to small changes in the wavelength of the laser emission. The main features predicted by theory are, however, clearly seen, although the resolution is insufficient to determine the structure of the central peak or ascribe a precise value to the width of the satellites.

Measurements made with the 5-Å bandwidth

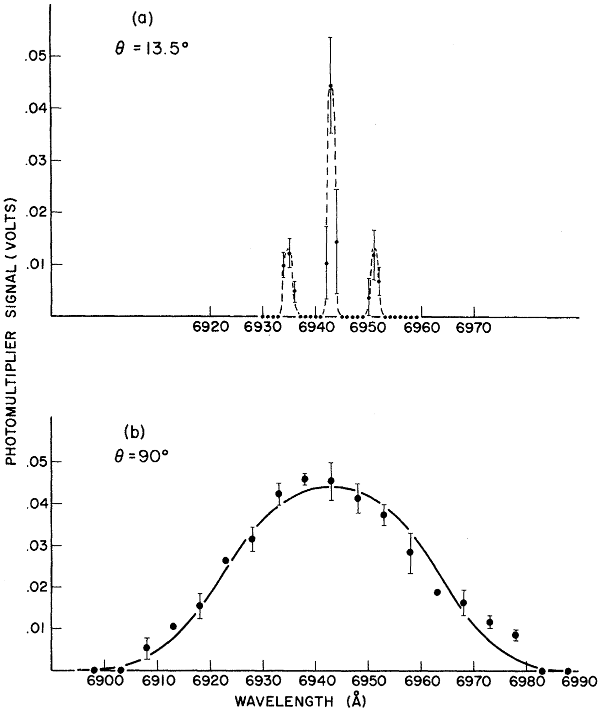

FIG. 2. Spectral distribution (difference between laser + plasma and laser alone) of radiation scattered at (a) $\theta = 13.5°$ and (b) $\theta = 90°$. The solid curve in (b) is the theoretical distribution for $n_e = 2.4\times 10^{15}$, $T_e = 1.0$ eV, $\alpha = 0.5$ fitted to the experimental data.

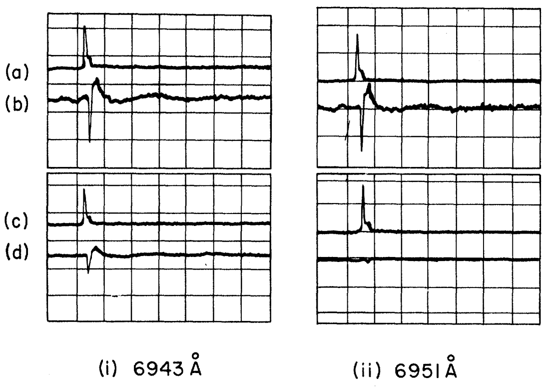

FIG. 3. Traces of oscillograph recordings for $\theta = 13.5°$ with 5-Å interference filter alone centered on (i) 6943 Å (with filter of neutral density 1.0), (ii) 6951 Å, and showing, (a) and (c) monitor pulses, (b) radiation scattered from the plasma, (d) stray light. Scales, 0.5 μsec/cm, 0.05 V/cm.

filter alone show much less scatter and yield an average value of 9.0 ± 1.5 for the ratio of the total intensity of the central peak to that of one satellite, corresponding to a value of $\alpha = 3.0 \pm 0.25$ for a thermal plasma. Typical results, showing the scattered radiation, monitor pulse, and stray light are presented in Fig. 3. The ratio of scattered radiation to stray light is ~3:1 in the central peak and ~10:1 at the satellites. The signal-to-noise ratio is good, even for the satellites. The overswing in the photomultiplier signals is due to the electrical filter used to discriminate against radiation from the plasma.

The wavelength shift (±8 Å) of the satellites corresponds, using Eq. (2), to an electron density of 2.4×10^{15} cm^{-3}. Using this value of the electron density, we obtain from Eq. (1) an electron temperature of 1.1 eV. These results are supported by measurements of the radiation scattered at right angles to the laser beam made, as described earlier,[2] using a double monochromator. Stray light in this direction is now negligible. The observed spectral distribution, Fig. 2(b), agrees well with the theoretical profile for $\theta = 90°$, $n_e = 2.4\times 10^{15}$cm^{-3}, $T_e = 1.0$ eV, $\alpha = 0.5$. Integrating to obtain the total intensity of the scattered radiation and comparing this with that scattered from nitrogen at a pressure of 1 atm, we obtain a value of $n_e = (2.4 \pm 0.5)\times 10^{15}$cm^{-3}.

It should be noted, however, that while the results are consistent with the assumption of a plasma in which $T_e = T_i$, the data yield direct evidence only for a thermal electron-velocity distribution and do not exclude the possibility that the temperature of the ions may differ from that of the electrons. Further measurements, particularly of the structure of the ion peak, are required to determine the ratio of the electron and ion temperatures.

We would like to thank Dr. F. Perkins for supplying us with calculations of the spectral distribution of the scattered radiation and for a number of useful discussions.

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EXTERNAL EXCITATION OF STANDING WAVES IN A RF DISCHARGE

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(Received 18 Januray 1966)

Experimental studies on the propagating density waves excited in a positive column of a dc discharge by a small coil surrounding the discharge tube were done by several authors.[1-5] Their results showed that there were two types of propagating waves in the positive column, i.e., the forward waves (ion acoustic waves) and the backward waves. This Letter reports experimental results on the waves excited by the same method but in a plasma produced by a rf discharge under the application of a weak axial magnetic field ($B_0 \leq 50$ G). The waves are standing waves, the wavelength of which is proportional to B_0, in contrast to the results observed in a dc discharge by the authors mentioned above.

The experimental apparatus is shown in Fig. 1. The gas used is mercury vapor at a pressure of about 1 μ Hg. The tube is filled with the plasma (plasma density $= 10^{10}$-10^{11} cm^{-3}, electron temperature $\sim 10^5$ °K) produced by a rf voltage at a frequency of about 15 Mc/sec. The homogeneity of the plasma is confirmed along the axial direction except for the place very close to the metal rings used for the rf discharge and the ends of the tube. The waves are detected by observing the fluctuation of light intensity led to a photomultiplier through an optical fiber, the diameter of which is about 3 mm, and the signals from the different positions are compared on a dual-beam synchroscope.

Without the steady axial magnetic field, no propagation of waves is detected. When the weak axial magnetic field is applied, the waves are excited symmetrically on both sides of

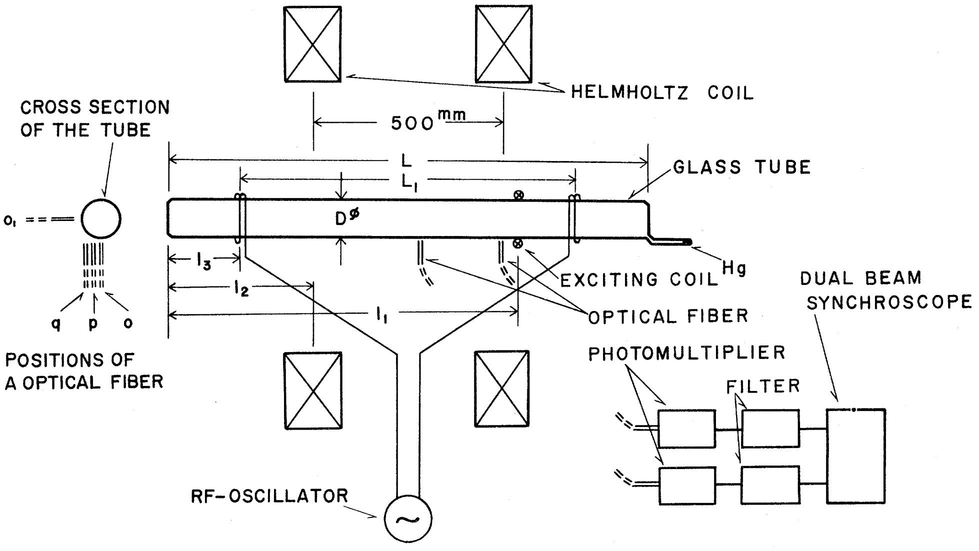

FIG. 1. The experimental apparatus.