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OBSERVATION OF THOMSON AND CO-OPERATIVE SCATTERING OF RUBY LASER LIGHT BY A PLASMA

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OBSERVATION OF THOMSON AND CO-OPERATIVE SCATTERING OF RUBY LASER LIGHT BY A PLASMA

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ABSTRACT

Light from a ruby laser has been used to demonstrate scattering by a plasma in each of the two principal domains for scattering, namely the Thomson domain, in which α, the ratio of scale length for scattering to plasma Debye length, is less than one, and the co-operative domain, in which α is greater than one. A pulsed arc in hydrogen was used to generate a plasma having Debye length 0.4 microns which permitted observation of the Thomson feature at 170° to the direction of incident light ($\alpha = 0.15$) and the co-operative feature at 10° ($\alpha = 1.7$). In the Thomson case, a Doppler broadened spectrum consistent with a gaussian distribution of half-width 70 Å corresponding to electron temperature of 2.2 eV was observed. Stray light from the laser was about one half of the scattered intensity at the centre of the distribution. At 10°, stray light was negligible and scattered light had a spectral width of less than 2 Å, the detector channel width, and an intensity consistent with the expected co-operative scattering cross-section.

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When monochromatic light is directed onto a plasma, a fraction of the light undergoes scattering on the free electrons, whose motion introduces Doppler broadening. A number of theoretical papers, e.g. Dougherty and Farley(1), Fejer(2) and Salpeter(3) have dealt with the problem of the resulting wavelength spectrum and have shown that it can be characterized by a single parameter

$$\alpha = \frac{\lambda}{4\pi D \sin \theta/2}$$

where λ is the wavelength of the incident light, D the plasma Debye length and θ the angle to the incident beam at which the light is scattered. Theory shows that for $\alpha << 1$ the spectrum takes the form of a Gaussian whose width is given by the average velocity of electrons at a temperature T_e, decreased by a geometrical factor, $\sin \theta/2$. This has been called incoherent or Thomson scattering. For $\alpha>1$ the electrons behave collectively and their motion is determined in part by the motion of the ions. The spectrum is expected to consist of a central feature whose width depends on the sound velocity in the plasma, together with two peaks shifted on either side of the centre by an amount given by the electron plasma wave velocity.

We have designed an experiment in which the correct choice of plasma parameters allows us to detect both the $(\alpha<<1)$ mode and the collective $(\alpha>1)$ mode in the same plasma merely by altering the direction from which scattered light is observed. The upper part of Figure 1 illustrates the experimental arrangement for observation of the $\alpha<<1$ feature. A Q-switched ruby laser produces a 2.5 MW pulse of light at 6935.5 Å having a spectral width of 0.05 Å(4) which is introduced into the plasma through a suitably baffled entry tube and is carried away through an exit tube which terminates in an efficient light trap.

The plasma is a pulsed hydrogen arc formed in 200 mTorr of hydrogen between a pair of stainless steel electrodes 50 cm apart. An axial magnetic field of 5 kgauss maintains the plasma for about 350 μsecs during which a peak current of about 20 kA flows. Stark broadening measurements of the Hβ line have given an electron density of 9×10^{14} cm^{-3} and subsequent measurements of the width of the $\alpha<<1$ feature gave an electron temperature $kT_e = 2.2$ eV. This means $\alpha<1$ for $\theta>16^{\circ}$. Observations were made at $170^{\circ} \pm 1.5^{\circ}$ and $10^{\circ} \pm 1.5^{\circ}$ for which $\alpha = 0.15$ and $\alpha = 1.7$ respectively. In both cases the detection optics were based upon a conical lens, placed concentric about the laser beam, which accepted all the light scattered at the preselected angle from the plasma. In the backscatter experiment, spectral resolution was obtained by tilting a nominally 3 Å band pass interference filter centred at 6943 Å. An E.M.I. 9558A photomultiplier with an S_{20} (trialkali) cathode response detected the light transmitted by the filter. The lower part of Figure 1 shows the experimental arrangements adopted for forward scattering measurements. The optical train and detector are essentially the same as before, but since the acoustic feature was expected to have a width of about 0.2 Å, the tilting filter was abandoned in favour of a scanning Fabry-Perot interferometer.

Figure 2 shows the results of the scattering experiment at 170°, and displays the total scattered signal as a function of wavelength. It therefore includes stray scattering of the main beam from the walls of the vessel etc. and this appears as an anomalous peak at the centre of the distribution. Measurements made in the absence of plasma (black circles) indicate that the stray light has been reduced to a manageably low level. The stray light spectrum, which is simply the instrumental shape of the filter and the detection optics, has been subtracted from the total signal and a Gaussian curve (half half-width 35 Å) has been fitted, from which it appears that the electron temperature $kT_e = 2.2$ eV.

Figure 3 displays the signal observed in the forward scatter position as a function of wavelength. In this case no correction for stray light was required since an observation made without plasma in the vessel showed that stray light and Rayleigh scattering on neutral hydrogen were undetectable. The spectral resolution of the system is restricted by the absolute light intensity available which has set a practical limit of 2 Å on the setting of the interferometer. The experimental points are consistent with an instrumental profile 2 Å wide, and one can regard this as an upper limit to the width of the feature being observed.

Nitrogen at a pressure of ¼ atmosphere was substituted for plasma in the chamber and the intensity of light at the detector due to Rayleigh scattering was measured. The ratio of intensities of Rayleigh scattered light and light scattered by the plasma was $S_r/S_t = 8.8$. The expected value of this ratio was calculated assuming the plasma scattered light to be associated with a cross-section equal to about ½ the Thomson cross-section, as predicted by the theory of co-operative scattering. Rayleigh cross-sections were taken from George et al.(5). The theoretical Rayleigh cross-section led to $S_r/S_t = 9.0$ and the experimentally determined cross-section gave $S_r/S_t = 21$. We conclude that the intensity of the signal observed in the forward scatter experiment is consistent with scattering by the acoustic wave.

The width, (<2 Å), is also consistent with acoustic wave scattering, and at the same time rules out the possibility that the light scattered at 10° is due simply to Thomson scattering, for if this were so a width of $\frac{\sin 10^{\circ}/2}{\sin 170^{\circ}/2} \times 70$ Å = 6 Å would be expected.

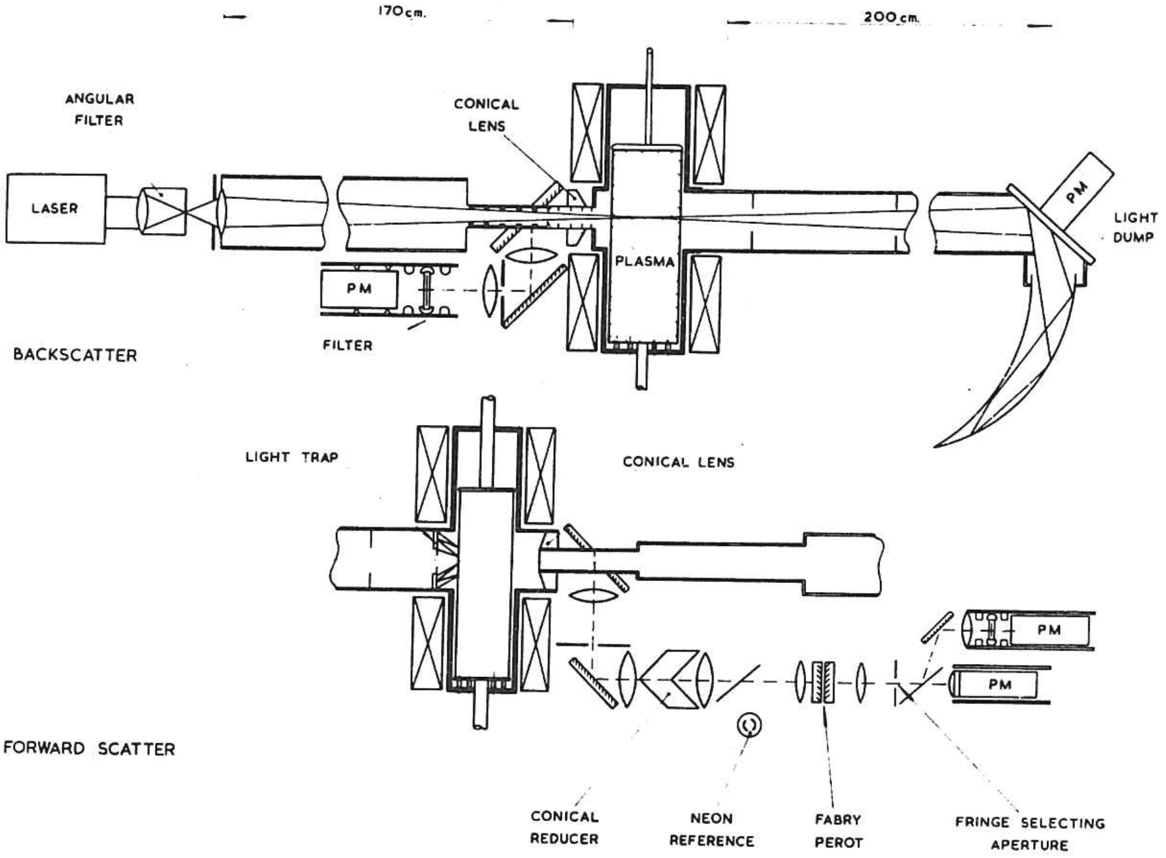
It remains possible that there is a contribution to the observed forward intensity due to some effect apart from co-operative scattering. Photoionization of neutral hydrogen followed by immediate radiative recombination could produce spurious photons, but there are unlikely to be many, owing to the very short relaxation time (10^{-10} secs.) compared to both the laser pulse length (2×10^{-8} secs) and the recombination time (10^{-2} secs). The intense electromagnetic field of the laser light in the plasma will produce photons at the laser frequency through stimulated emission of radiation. These will however be in phase with the stimulating field, and so will travel in the same direction as the principal laser beam. Again, only a negligible number is expected to reach the detector.

Work is proceeding to improve the strength of the forward scattered signal with the aims of measuring the width of the central peak and of detecting the satellites at the plasma frequency.

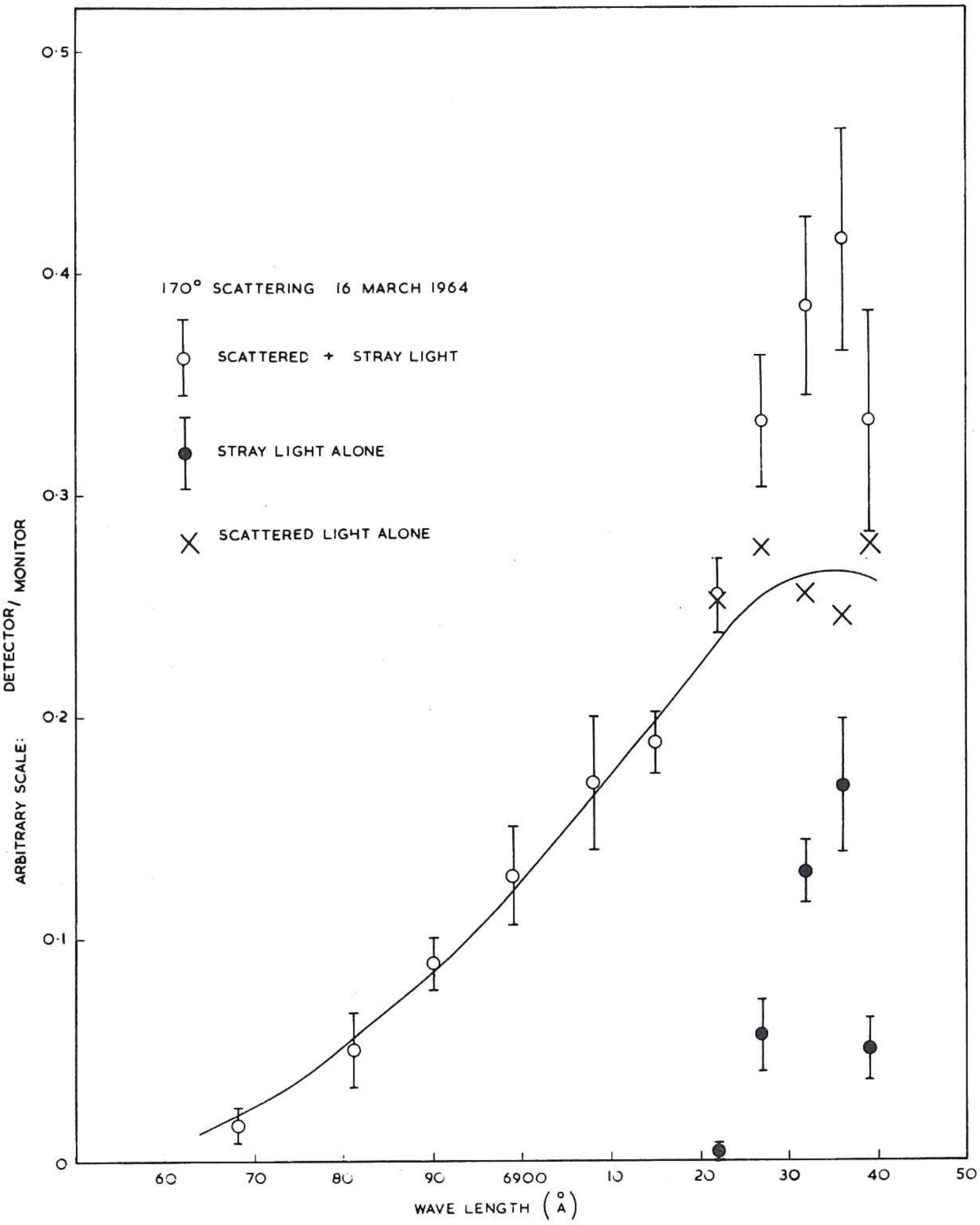
We wish to acknowledge our indebtedness to Dr. R. Wilson for suggesting the problem, doing the initial feasibility study, and providing constant encouragement through discussion. We are also indebted to Dr. D.J. Bradley who has given advice on problems of optics and interferometry. One of us, A.W. DeSilva, gratefully acknowledges the support of the National Science Foundation during a major part of the work.

REFERENCES

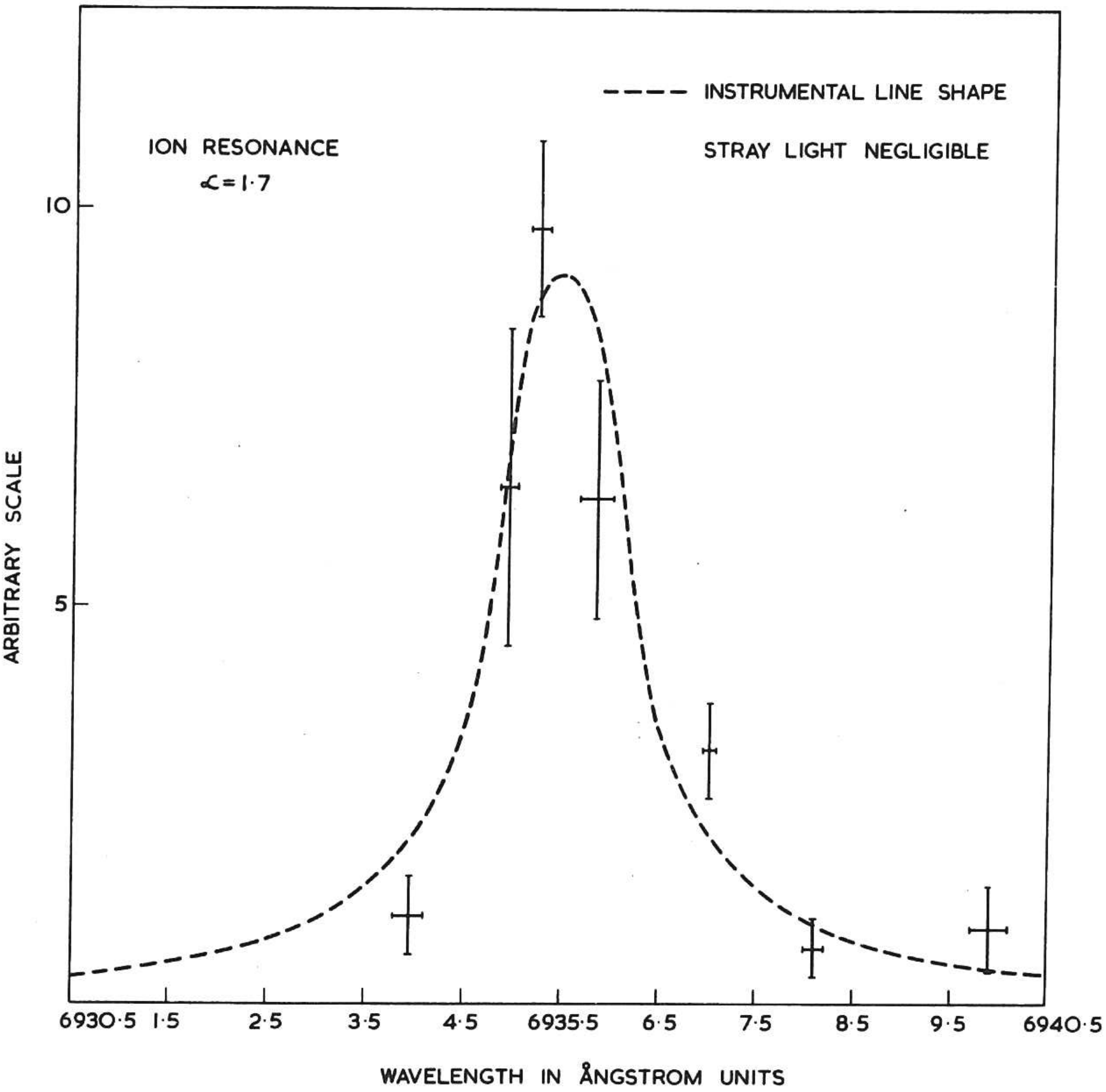
1. J.P. Dougherty and D.T. Farley, Proc. Roy. Soc. A.259, 79, (1960).
2. J.A. Fejer, Con. J. Phys., 38, 1114, (1960).
3. E.E. Salpeter, Phys. Rev., 120, 1528, (1960).
4. D.J. Bradley, A.W. DeSilva, D.E. Evans and M.J. Forrest, Nature, 199, 1281, (1963).
5. T.V. George, L. Shama, M. Yokoyama, L. Goldstein, Phys. Rev. Letts., 11, 403 (1963).



CLM - P 57 Fig. 1
Schematic of experimental layout



CLM-P 57 Fig. 2
Spectrum of light scattered at 170°. Laser wavelength 6935.5 Å



CLM - P 57 Fig. 3
Spectrum of light scattered at 10°. Laser centred at 6935.5 Å