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LIGHT SCATTERING BY PLASMAS

by

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(Submitted for publication in Physics Letters)

A B S T R A C T

The assertion of Nguyen-Quang-Dong [1] that experiments on light scattering in plasmas have invalidated the theory used to interpret them is rejected. In almost all instances the spectrum of scattered light may indeed be characterized by the parameter α defined by Salpeter [2].

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In treating the scattering of radiation by plasmas Salpeter has defined a parameter of importance in the theory

$$\alpha = \frac{k_D}{k} = \frac{k_D \lambda}{4\pi \sin \theta/2} \qquad \ldots (1)$$

where k_D is the Debye wave number for the plasma, k , λ , the wave number and wavelength of the incident radiation and θ the angle between the directions of the incident and scattered radiation. The results of this calculation showed that when $\alpha > 1$ the spectrum of scattered radiation departs from the Gaussian line profile (with a width determined by the electron temperature) found for plasmas in equilibrium with $\alpha << 1$, the line shape now being determined by collective effects in the plasma. This theory has been used to interpret the results of experiments on the scattering of laser light by a variety of laboratory plasmas in which both the low-frequency ion acoustic resonance [3,4,5,6] as well as that at the electron plasma frequency [6,7,8,9] have been observed. In a recent Letter [1] Nguyen-Quang-Dong claims that experimental work has invalidated, rather than confirmed the theory which he criticizes on the grounds that "Salpeter's affirmation that the Coulomb correlation is intrinsically related to α is incorrect." While recognizing that α characterizes the experimental conditions under which correlation effects manifest themselves, Nguyen-Quang-Dong emphasizes that the parameter which is the measure of the correlations is <u>not</u> α but rather $\Lambda = k_D{}^3/N$ where N is the plasma electron density.

The determination of the spectrum of scattered radiation involves essentially the calculation of the conductivity tensor for the plasma, and in doing this an expansion in powers of Λ , the plasma parameter, is introduced. Retaining only the first term of this expansion is equivalent to the random-phase (R.P.) approximation (in which one neglects the interaction between modes of different wave-number) and is the procedure adopted by Salpeter. To this level of approximation the profile of the feature in the scattered light spectrum at the electron plasma frequency, ω_p, is Lorentzian with a width, $\Delta\omega_L$, determined by the electron Landau damping:

$$\Delta\omega_L \sim 0.28\, \omega_p\, \alpha^3 \exp(-\alpha^2/2) \qquad \ldots (2)$$

i.e. provided Λ is a good expansion parameter, (2) represents the dominant contribution to the line width <u>except</u> in the case of plasma oscillations of long wavelengths when $\Delta\omega_L \to 0$. Then Landau damping ceases to be the dominant absorption mechanism; it is supplanted by the two-particle collision process and the determination of the profile of the feature at the electron plasma frequency now requires that the calculation of the conductivity tensor be carried through to next order in Λ i.e. beyond the R.P. approximation used by Salpeter. This has been done and leads, in the frequency region $\omega \simeq \omega_p$, to a line width $\Delta\omega_C$ given by [10,11,12]

$$\Delta\omega_C \simeq 0.02\, \omega_p\, \Lambda \ln \Lambda^{-1} \qquad \ldots (3)$$

This represents the effect of close Coulomb collisions* on the line-width and is the factor determining that width whenever $\alpha > \alpha_o$ (cf. [12]) where

$$13\, \alpha_o^3 \exp(-\alpha_o^2/2) = \Lambda \ln \Lambda^{-1}, \quad (\Lambda << 1) \qquad \ldots (4)$$

i.e. for sufficiently small k or, from (1), whenever one carries out the scattering experiment very close to the forward ($\theta = 0$) direction.

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* The collision process of importance in the $O(\Lambda)$ correction term is the electron-ion one. Ion-ion and ion-electron collisions are, of course unimportant; electron-electron collisions lead to an $O(\Lambda)$ correction which has a k^2 dependence and so the contribution from this is unimportant in the long wavelength limit.

It is clear from Table 1 that by using parameters referring to experiments carried out to date the contribution to the broadening from (3) is wholly negligible. An exception is the work of Chan and Nodwell [9] in which $\Lambda \sim 0.47$ and so the weak-coupling approximation $(\Lambda << 1)$ is no longer adequate.*

Nguyen-Quang-Dong's remark that for Λ very small and $\alpha \geqslant 1$ Salpeter's prediction would be incorrect is untrue in general; what is true is that for $\alpha > \alpha_o$ one must take account of $O(\Lambda)$ terms in computing the scattered radiation spectrum as Salpeter himself acknowledges.

TABLE 1

Reference	α	Λ	$\Delta\omega_L/\omega_p$	$\Delta\omega_C/\omega_p$
Kunze [5]	1.0	0.050	0.17	0.003
DeSilva et al [3]	1.7	0.022	0.30	0.002
Ramsden, Davies [8]	3.0	0.010	0.08	0.005
Chan, Nodwell [9]	4.5	0.047	0.001	0.007
Evans et al [7]	1.5	10^{-4}	0.30	2.0×10^{-5}
Anderson [6]	1.4	0.16	0.29	0.006

So far we have not mentioned the effect of Coulomb collisions on the low-frequency resonance in the scattered light spectrum. The collisionless theory is valid whenever $kV_i^{th} >> \nu_{ee}$ where V_i^{th} is the ion thermal speed in the plasma and ν_{ee} the electron-electron

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* For most of the other experiments one would have to look at angles so small as to be unattainable in practice before collision broadening becomes dominant over the line width determined by Landau damping. It happens in the Ramsden-Davies experiment [8] that $\Delta\omega_L \lesssim \Delta\omega_C$ for values of $\theta \lesssim 10^o$. In principle in this experiment one could pass from the regime in which the line-width is determined by [2] to that in which [3] represents the dominant contribution. The line-widths of course are then extremely narrow (of the order of 0.04 Å) and, with present laser technology, at the limits of resolution.

collision frequency i.e. provided

$$\alpha \Lambda \ln \Lambda^{-1} << \left(\frac{m}{M}\right)^{\frac{1}{2}} \qquad \ldots (5)$$

$\frac{m}{M}$ being the electron/ion mass ratio. The opposite limit of collision-dominated plasmas has been considered by DuBois and Gilinsky [10] and by Boyd [12]. In this case the ion feature is considerably sharper than the profile for the collisionless plasma in equilibrium. For values of α , Λ such that

$$\left(\frac{m}{M}\right)^{\frac{1}{2}} < \alpha \Lambda \ln \Lambda^{-1} < 1 \qquad \ldots (6)$$

one expects the profile of the low-frequency resonance in the scattered spectrum to be intermediate between these two limits. In passing one may note that in three recent observations criterion (5) is well satisfied in the work of Evans, Forrest and Katzenstein [13] and in one of two cases discussed by Ramsden, Benesch, Davies and John [14]. For one set of parameters in the experiments of Kronast and his associates [15] $\alpha \Lambda \ln \Lambda^{-1}$ lies in the region given by (6) so that in this case an interpretation of the experimental data in terms of the collisionless theory may be inconsistent.

Finally, Nguyen-Quang-Dong asserts that the results of Consoli et al [16] prove that the effects of correlations come into play, regardless of the value of α . One expects, of course, that for values of $\alpha \lesssim 1$ there will indeed be some degree of correlation and hence slight deviations from a Gaussian profile. Consoli et al, for $\alpha \sim 0.3$, find that the electron temperature, T_e , from scattering measurements lies between 16,000°K and 38,000°K while Stark measurements give 28,000°K - 40,000°K. The conclusion of Consoli and his associates is that there is agreement between the two measurements within the limits of experimental error. Further deviations from a Gaussian profile may occur in work by Kunze and others [17] in which $\alpha = 0.53$. However, if one examines experiments in which $\alpha << 1$

(cf. DeSilva, Evans and Forrest [3] with $\alpha = 0.15$ and Gerry and Rose [18] with $\alpha \sim 0.09$) there would appear to be no deviations from a Gaussian spectrum within the limits of experimental error.

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