Density Fluctuation Spectra of a Collision-Dominated Plasma Measured by Light Scattering

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The low-frequency electron density spectral function $S(k,\omega)$, having an ion acoustic peak (at $\omega \sim kC_s$) and an entropy peak ($\omega = 0$), has been measured by light scattering in a thermal collisional argon arc plasma. The entropy peak is observed in a plasma for the first time. A prediction of the spectrum derived from Braginskii's equation is adopted to estimate the transport coefficients. The ion viscosity, ion thermal conductivity, and electron-ion energy-transfer frequency determined from fitting to the data differ from predictions by −39%, +16%, and −22%, respectively.

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The electron density fluctuation spectrum $S(k,\omega)$ of a collisional plasma is a fundamental quantity closely related to transport properties. Previous measurements of $S(k,\omega)$ in collisional-dominated plasmas failed to resolve structure near zero frequency,[1-5] and theories of this regime are not in agreement.[6-10] We report here observation of $S(k,\omega)$ in the low-frequency region for a collisional plasma in near equilibrium by means of CO_2 laser light scattering. The observed spectrum consists of three peaks, two representing ion acoustic waves propagating in the opposite directions, and the third a nonpropagating peak centered at zero frequency and attributed to entropy fluctuations. The ion acoustic fluctuations have been previously observed,[1-5] but the observation of the entropy fluctuations in a plasma has not heretofore been reported, although such fluctuations are well known in ordinary fluids.[11]

Most theories of the electron density fluctuation spectrum of a collisional plasma[6-8] predict collisional narrowing of the ion acoustic peaks, which are heavily Landau damped in a collisionless plasma, and the appearance of the zero-frequency peak. Two theories[9,10] suggest that collisions cause the ion acoustic peaks to broaden further and merge into a single featureless peak.

In Ref. 1, in which only the ion acoustic peaks were observed, it was concluded that the Bhatnagar-Gross-Krook kinetic theory,[7] modified for adiabatic rather than isothermal density fluctuations, gave the best fit to experiment. However, this theory fails to account for electron-ion collisions. A one-fluid theory of Mountain[12] also gave a moderately good fit to experiment. This theory relates the shapes of the scattering features to transport coefficients, but is clearly of limited use when applied to a plasma, where transport effects of electrons and ions are quite different. In the present experimental work the frequency of the slowest collisional process (ion-ion) exceeds even the highest fluctuation frequencies in the ion acoustic features, so it appears that a fluid theory would be applicable. We have accordingly calculated the fluctuation spectrum from the two-fluid theory of Braginskii[13] and have compared several transport coefficients from this theory to the experimental data.

For a highly collisional plasma, the equations of Braginskii may be applied to calculate an ac electrical conductivity, which is then used in the fluctuation-dissipation theorem to obtain the electron density fluctuation spectrum. The process is analogous to that employed by DuBois and Gilinsky.[6]

An exact analytic expression for the spectrum may be obtained, but it is rather cumbersome. Under the conditions of low frequency and long wavelength ($\omega \lesssim kC_s$, $k \ll k_D$, where k is the wave vector of the density fluctuations, $C_s^2 = T/m_i$, and k_D is the Debye wave vector), and in the absence of a magnetic field, the expression may be approximated as

$$S(k,\omega) = 2n_e \frac{A + B\beta^i/D(\omega)}{[A + B\beta^i/D(\omega)]^2\omega^2 + [2 - \omega^2/\omega_s^2 + \frac{3}{2}B\omega^2/D(\omega)]^2}, \tag{1}$$

where

$$A(k) = \frac{n_e}{k^2\kappa^e} + \frac{4}{3}\frac{\eta_0^i}{n_e T}, \tag{1a}$$

$$B(k) = \frac{n_e}{k^2\kappa^e} C_{ie} + 1, \tag{1b}$$

$$D(\omega) = (\beta^i)^2 + (\tfrac{3}{2}\omega)^2, \tag{1c}$$

and

$$\beta^i = k^2\kappa^i/n_e + C_{ie}, \quad \omega_s = kC_s. \tag{1d}$$

$C_{ie} = 3m_e/m_i\tau_e$ is the collisional energy-transfer frequency of the plasma; τ_e is the electron collisional time; η_e is the electron density; and κ^i, κ^e, and n_0^i are the ion and electron thermal conductivities and ion viscosity coefficient, respectively. Equation (1) predicts the threepeaked spectrum observed.

Calculation reveals that in the entropy fluctuation frequency region, the high electron thermal conductivity prevents the electron temperature from fluctuating significantly compared with the ion temperature ($|\delta T_e|/|\delta T_i| \lesssim 0.05$). The damping of this mode is then through two channels: ion thermal conduction and collisional energy transfer between ion and electron fluids. The width of the fluctuation peaks is determined by the damping. In the case of $(\beta^i)^2 \ll (kC_s)^2$, the width of the entropy peak may be determined as

$$\delta\omega_{\text{entropy}} = \frac{2\beta^i}{3+B} = \frac{2}{3+B}\left[\frac{k^2\kappa^i}{n_e} + C_{ie}\right],$$

where the first term is due to ion thermal conduction and the second term to energy transfer between ions and electrons. For large k, ion thermal conduction will dominate damping because the temperature gradient is proportional to k. When k approaches zero, the width of the entropy peak will reach a constant which is determined by the energy transfer between ions and electrons.

Under the conditions $(\beta^i)^2 \ll (kC_s)^2$ and $A \ll 1/kC_s$, the ion acoustic peaks assume Lorentzian forms,

$$S(k,\omega) \to \frac{n_e}{\gamma}\frac{\Gamma k^2}{(\Gamma k^2)^2 + (\omega-\omega_r)^2},$$

where

$$\Gamma k^2 = \frac{Ak^2T}{2m_i} + \frac{B\beta^i}{9\gamma},$$

$$\omega_r = (2\gamma)^{1/2}\omega_s\left[1 - \frac{B(\beta^i)^2 m_i}{27\gamma^2k^2T} - \frac{A}{8\gamma^2}\left[\frac{2B\beta^i}{9} + A\gamma k^2\frac{T}{m_i}\right]\right],$$

$$\gamma = 1 + B/3.$$

Calculations show that the damping of the ion acoustic resonance is mainly affected by the ion viscosity and ion thermal conductivity. Landau damping is, of course, not included in this theory, but it is assumed to have negligible effect for the large collision frequencies encountered in the present experiments. This assertion has been tested in a simulation program that determines the mean rate of energy transfer between propagating waves and resonant ions. The result is that for the conditions of this work, the energy-transfer rate is down by more than 2 orders of magnitude from its level in a collision-free plasma. The electron thermal conductivity may have a perceptible effect on the damping when the wave vector k is very small [$k \lesssim n_e(T/\kappa^e\eta_0^i)^{1/2}$]. Increasing ion viscosity or ion thermal conductivity would broaden the width of the ion acoustic peaks, while larger electron thermal conductivity would make the peaks slightly narrower.

The theory and practice of light-scattering measurement of electron density fluctuations in a plasma are described in references contained in Ref. 1. For a given scattering angle θ, the propagation wave vector k of the fluctuation responsible for the resultant scattering is given by the Bragg scattering condition $k = 2k_0\sin(\theta/2)$, where k_0 is the wave vector of the probing radiation. The scattered light undergoes Doppler frequency shifts according to the frequency spectrum of the fluctuations at wave vector k, so the fluctuation spectrum reveals itself in the frequency spectrum of the scattered light.

In order to measure the effects of the collisions on the collective ion fluctuation spectrum, the wavelength of the probing radiation has to be longer than the Debye length ($k_0 < k_D$) to ensure that the scattered light comes from the collective fluctuation rather than from the discrete fluctuations, and the spectrum must be in the collisional regime ($\nu_{ii} > kC_s$). High-density, low-temperature plasmas and long-wavelength probing radiation and small scattering angle are required to fulfill the above conditions.

We have used 10.6-μm radiation from a pulsed CO_2 laser to probe an argon plasma created in a pulsed arc (pulse length $=100$ μsec), having density $n = (1.0 \pm 0.1)\times 10^{17}$ cm^{-3}, and temperature $T_e = T_i = 1.95^{+0.15}_{-0.05}$ eV. Equality of electron and ion temperatures is assured by the short equilibration time, about 2 nsec.[14] Plasma conditions were diagnosed by emission spectroscopy and interferometry, and experimental checks established the absence of significant nonthermal fluctuations.[1] The plasma composition was deduced from the Saha equation to be $n_e{:}n_0{:}n_+{:}n_{++} = 1.16{:}0.01{:}0.84{:}0.16$. The local-thermodynamic-equilibrium (LTE) validity criteria of Griem are just satisfied when the optical thickness of the resonance lines is taken into account.[15] The effect of slight departures from LTE would be to lower the fraction in the second ionized state.

Scattering angles of from 5° to 10° are used, and the conditions mentioned above ($k_0/k_D \sim 0.01$–0.02, $\nu_{ii}/kC_s \gtrsim 7$) are fully satisfied.

The scattered light frequency spectra are measured using an optical heterodyne system. The experimental scheme is modified from that of Ref. 1 by shifting the frequency of the local oscillator beam by 47 MHz with a Bragg cell. A resultant spectrum received by the heterodyne detection system is thus translated by 47 MHz; hence the zero-frequency spectrum is represented in the detection system in a frequency region at 47 MHz, well separated from the extremely noisy zero-frequency region. Owing to the presence of a comparably large stray scattered light component appearing at 47 MHz, it was necessary to use a narrow-band (2 MHz) notch filter centered at 47 MHz in the detector output to prevent saturation of the following electronics.

The spectra from scattering angles of 4.70 ± 0.15 and 8.70 ± 0.15 have been observed. Figures 1(a) and 1(b) show the spectra at scattering angles of 4.7° and 8.7°.

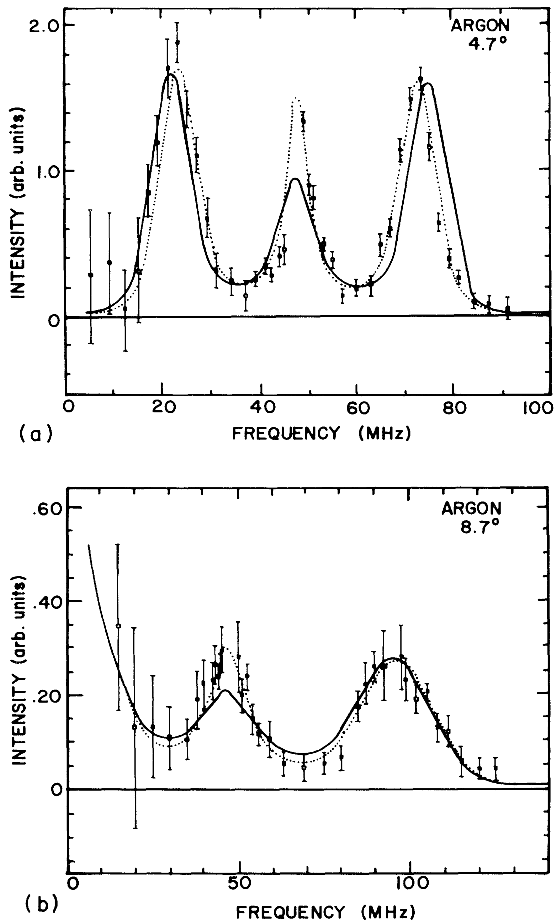

FIG. 1. Scattered light spectra of argon plasma at a scattering angle of 4.7° and 8.7° (see text). The solid lines are the prediction of two-fluid theory of Braginskii, with the only adjustable parameter being intensity. The dotted lines are the best fit obtained by adjusting the transport coefficients of the theory.

The central peaks, appearing frequency shifted to 47 MHz, are due to the entropy fluctuations, and the peaks appearing at the two sides are due to ion acoustic waves propagating in opposite directions. Since the ion acoustic peaks are separated by about 100 MHz in the 8.7° case, the left-hand peak falls almost on the zero frequency of the detector output, so its remote wing is folded over onto its inner wing. The solid lines superposed on the data are the theoretical prediction from the two-fluid theory [Eq. (1)] computed for the measured plasma conditions assuming $Z=1$, in which the detection system broadening, amounting to ~ 1 MHz for the entropy peak and 3 (4) MHz for the 4.7° (8.7°) ion acoustic peaks, has already been included. The only adjustable parameter used is the amplitude scale of the theory. The transport coefficients and viscosities entering into the theory are those computed from Braginskii.[13] It is evident that the ion acoustic peak positions are not well modeled, nor is the height of the entropy peak.

Taking the attitude that a two-fluid theory is valid for this plasma, and that the discrepancies between theory and experiment are due to imperfect models for the transport coefficients, we have performed a second-fitting procedure, in which the transport coefficients are treated as variables to be determined by a best fit to the experimental data. Equation (1) was accordingly fitted to the experimental data by least-squares fitting, with the parameters κ^i, κ^e, η_0^i C_{ie}, and ω_s and the amplitude scale treated to be adjustable. The fit is indicated by the dotted lines in Figs. 1(a) and 1(b), and is clearly better than the former fit. The resultant parameters are listed and compared with Braginskii's values in Table I. Because the spectrum is not sensitive to the electron thermal conductivity, κ^e cannot be well determined by the fitting process, as is seen by the large error on its upper limit. In order to estimate the electron thermal conductivity precisely, smaller scattering angles or longer-wavelength probing radiation may be required to obtain spectra with smaller wave vector k, in which the effect from electron thermal conduction may become significant.

The resultant value of ion thermal conductivity from the fitting is about 40% smaller than Braginskii's prediction. The experimental value of ω_s, the position of the ion acoustic peaks, agrees quite accurately with Braginskii's value for 8.7° scattering, while it is about 8% smaller than the prediction for 4.7° scattering. The ion viscosity coefficient η_0^i and the energy-transfer frequency C_{ie} agree reasonably with the Braginskii values.

Braginskii's theory does not account for more than one ion species. In order to estimate the effects of A_r^{++} on the average ion thermal conductivity, we calculated an effective ion collision time averaged over all ions, assuming 16% second-stage ionization. The effective ion thermal conductivity calculated using this effective collision time is 8.7×10^{18} $\mathrm{sec}^{-1}\mathrm{cm}^{-1}$ which is about 37%

TABLE I. The resultant parameters from least-square fitting. Errors in the last column reflect the uncertainties of the measured values of T and n.

	κ^i (1/sec cm)	κ^e (1/sec cm)	η_0^i (g/cm sec)	$\omega_0(4.7°)$ (rad/sec)	$\omega_0(8.7°)$ (rad/sec)	C_{ie} (1/sec)
Experimental	$(0.84^{+0.23}_{-0.24})\times10^{19}$	$(0.7^{+1503}_{-0.5})\times10^{21}$	$(2.62^{+0.56}_{-1.46})\times10^{-4}$	$(0.967^{+0.006}_{-0.005})\times10^{8}$	$(1.978^{+0.048}_{-0.045})\times10^{8}$	$(1.63^{+1.02}_{-1.03})\times10^{7}$
Braginskii ($Z=1$)	$(1.37^{+0.32}_{-0.11})\times10^{19}$	$(2.13^{+0.49}_{-0.16})\times10^{21}$	$(2.26^{+0.52}_{-0.17})\times10^{-4}$	$(1.05^{+0.05}_{-0.02})\times10^{8}$	$(1.94^{+0.09}_{-0.03})\times10^{8}$	$(2.08^{+0.10}_{-0.29})\times10^{7}$

below Braginskii's prediction for a pure A_r^+ species, and agrees remarkably with the resultant value from the fitting process. However, the presence of A_r^{++} species would also affect the values of C_{ie} and η_0^i. The calculated values of C_{ie} and η_0^i using the same approach are, respectively, about 18% above and 37% below the predictions for pure singly ionized plasma, in both cases making the fit of theory to experiment worse. In order to accurately include the effects of the second-stage ionization in the density fluctuation spectrum, a three-fluid theory, with its third fluid to be the A_r^{++} species, may be needed. Such a three-fluid model has not yet been developed.

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