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OBSERVATION OF FIRST-ORDER ION ENERGY DISTRIBUTION IN ION-ACOUSTIC WAVES*

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The perturbed part of the ion distribution function is observed experimentally, when an ion-acoustic wave is excited in a plasma.

It has been recognized that plasma waves can be damped even in a collisionless plasma.[1] This collisionless damping (Landau damping) has been demonstrated experimentally.[2,3] Furthermore, Landau's theory shows that though the macroscopic quantities such as the electric field and the particle densities are damped exponentially, the perturbations in particle phase-space distributions oscillate indefinitely. Recent theory of plasma-wave echoes[4-6] and their experimental observations[7-10] confirm this fact indirectly. This paper reports direct observations of the perturbations in the ion distribution when an ion-acoustic wave is excited.

The basic properties of the perturbed ion distribution function are as follows. For the sake of simplicity, we limit the presentation to one dimension. If we excite an ion-acoustic wave in space at $x=0$ and at a frequency ω, the ω component of the ion distribution function as derived from the Vlasov equation is

$$f_\omega(v,x)=e^{-i\omega x/v}\left[\frac{e}{M}\frac{1}{v}\frac{\partial f_0(v)}{\partial v}\int_{+0}^{x}E(x')\times e^{i\omega x'/v}dx'+f_\omega(v,x=+0)\right]. \quad (1)$$

Here $E(x)$ is the wave electric field which can be calculated by using Poisson's equation, and $f_0(v)$ is the unperturbed distribution function. If the electron-to-ion temperature ratio T_e/T_i is about 1, $E(x)$ damps after a few wavelengths of propagation.[2,11-13] Therefore, f_ω has the form

$$f_\omega(v,x)=g(v)\exp(-i\omega x/v), \quad (2)$$

for large distances. Here, $g(v)$ is a slowly varying function. The main feature of f_ω is represented by the phase factor $\exp(-i\omega x/v)$ which reveals rapid oscillations in velocity space.

In order to make f_ω as large as possible within the applicability of the linear theory, and to obtain heavy Landau damping, a plasma with low T_e/T_i is employed in the experiment. The schematic diagram of the experimental arrangement is shown in Fig. 1. The plasma chamber is divided into two parts by a negatively biased mesh grid. The ions produced in the left part of the chamber by an argon discharge pass through the grid, and are neutralized by the electrons which are emitted from four filaments placed close to the wall in the right-hand part of the chamber. A high-frequency voltage (2 MHz, and 20 V peak to peak) applied to the grid scatters the ions in velocity when they pass through the grid. By adjusting the high-frequency voltage and the filament potential, a plasma with a half-Maxwellian

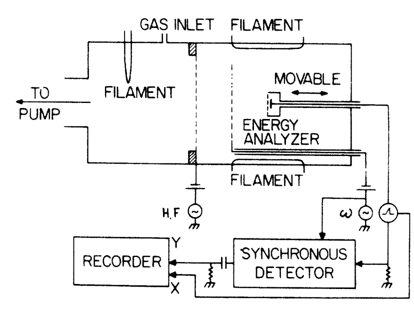

FIG. 1. Schematic diagram of the experimental arrangement.

ion distribution is obtained. The ion and the electron temperatures are 3 and 1.5 eV, respectively. The plasma density is from 10^9 to 10^{10} cm^{-3}. The neutral argon pressure is $(2\text{-}5)\times10^{-4}$ Torr.

An electrostatic energy analyzer is employed in order to observe f_ω as well as f_0. It consists of a fine-mesh grid (0.25×0.25 mm mesh size) and a collector. The separation between the two electrodes is about 1 mm. The grid is biased negatively with respect to the plasma potential, and repels the electrons. The energy selection of the ions which pass through the grid is performed by changing the collector potential φ (with respect to the plasma potential). The ion-current signal from the collector is fed to a synchronous detector. The output signal of the detector is differentiated with respect to φ, so that the final signal is proportional to $f_\omega((2e\varphi/M)^{1/2},x)$. The energy resolution of the analyzer, tested by using an afterglow plasma, is better than 0.1 eV.

The ion-acoustic wave is excited by a grid[2,13] (15 cm diam, and 0.25×0.25 mm mesh size). The frequency range studied is between 100 and 600 kHz. The propagation of ion-acoustic waves shows heavy collisionless damping. The e-folding damping length divided by the wavelength, $\delta/\lambda=0.6$, is almost independent of the frequency. The phase velocity is 5.5×10^5 cm/sec.

Figure 2 shows typical recorder output demonstrating the observation of f_ω as a function of energy. As expected from Eq. (2), the more rapid oscillations in velocity space are observed for larger distances. The wave excitation voltage, φ_{exc}, is 3 V peak to peak. Changes in φ_{exc} around this value do not introduce any difference in the shape of the observed f_ω. The amplitude of f_ω is linearly proportional to φ_{exc}. The shape of f_ω is found to depend strongly on f_0. If the high-frequency voltage is removed from the grid dividing the chamber, the higher energy tail of f_0 disappears. In this case, the amplitude of f_ω is very small at higher energies.

The phase relation,

$$\theta=\omega x/(2e\varphi/M)^{1/2}, \tag{3}$$

is confirmed in Fig. 3. The energy values of f_ω at various zero crossings are plotted as a function of the distance, x, in Fig. 3(a). Closed and open circles correspond to positive- and negative-going zero crossings of the observed f_ω curves, respectively. Any two solid lines adjacent to each other correspond to a phase difference of 2π. Figure 3(a) confirms that φ is proportional to x^2 for constant θ. By using plots similar to Fig. 3(a) for different frequencies, the relations between θ and x are plotted in Fig. 3(b), when $e\varphi$ is kept constant at 5 eV. Solid lines indicate Eq. (3). A constant phase angle is added to all of the experimental points so that they fall on a solid line.

The e-folding attenuation length, l, of f_ω for

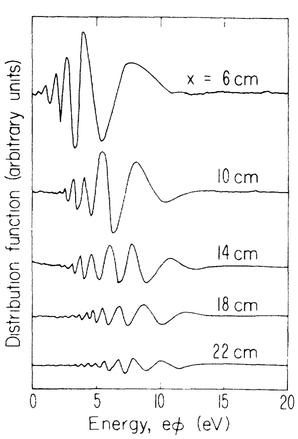

FIG. 2. Typical recorder output demonstrating f_ω as a function of energy. The wave frequency is 300 kHz. The plasma density is 6×10^9 cm^{-3}. Argon gas pressure is 2.5×10^{-4} Torr.

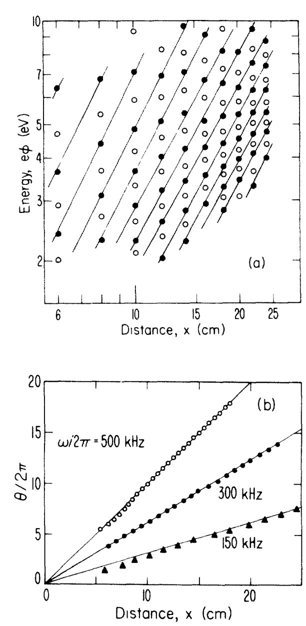

FIG. 3. (a) Energy values of f_ω at various zero crossings as a function of the distance, x. Closed and open circles correspond to positive- and negative-going zero crossings, respectively. The wave frequency is 300 kHz. (b) Dependence of the phase of f_ω on distance, x, for three different frequencies at $e\varphi=5$ eV.

higher energies ($e\varphi \gtrsim 5$ eV) is 8 cm for the data presented in Fig. 2 and is independent of the frequency of excitation. At higher neutral pressure this distance is reduced. This length corresponds to the ion-neutral collision mean free path, and is much longer than the damping length of the wave. For lower ion energies, however, l is smaller than that for higher ion energies. The low-energy l decreases as the frequency is increased. This behavior of the damping length with frequency in the lower ion energy range suggests that ion-ion collision effects are present.[9,14,15] Further improvement of the resolution of the energy analyzer will make it possible to measure the ion-ion collision effects as a function of energy. An experimental study of nonlinear effects on the distribution function should also be interesting.

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CONVERGENCE OF COUPLING-PARAMETER EXPANSIONS FOR DISTRIBUTION AND THERMODYNAMIC FUNCTIONS

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It is shown that Maclaurin expansions of properly defined distribution functions and of the density-to-activity ratio in powers of exponential coupling parameters (which multiply the Ursell-Mayer f bonds, instead of pair potentials) converge if the integral of the f bond over all space exists. Therefore various successive approximation schemes can be devised with the assurance that they will converge to the correct solution.

The device of multiplying the interaction potential of one or more particles by a coupling parameter whose value varies from zero (complete decoupling) to unity (full coupling) has been extensively used in quantum as well as classical statistics. Most problems dealt with by this method have been solved only in the weak (linear in the coupling parameters)-coupling limit; for example, for the case of Coulombic potentials, one obtains the Debye distribution.[1] One of the most serious difficulties in extending the method to include higher powers of coupling parameters has been the question of convergence of expansions of distribution and thermodynamic functions in powers of the coupling parameters of one or more particles: It was not known whether such expansions converge.

In this note we prove that expansions of properly chosen distribution and thermodynamic functions in powers of the exponential coupling parameters[2] (multiplying the Ursell-Mayer f bonds of individual particle pairs) of <u>any number</u> of particles of the system converge for <u>all positive values of the parameters</u>, for all classical systems for which the integral of the Ursell-Mayer f bond over an infinite volume is finite. We also show that expansions in powers of the usual coupling parameters (multiplying