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Observation of a Parametric Instability near the Lower Hybrid-Resonance Frequency*

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A parametric instability is observed at frequencies close to and above the lower hybrid-resonance frequency. The threshold occurs when the electron drift velocity is of the order of the plasma sound speed. At pump-power levels well above threshold the energy in the decay waves is comparable to that associated with the pump wave.

The possibility of heating plasma at frequencies near the lower hybrid resonance has been stressed for many years.[1] Experimental evidence of ion and electron heating at this frequency has been reported recently.[2] The nature of the heating process, however, remains unclear. According to linear theory,[3,4] near the lower hybrid resonance these waves will convert into a very short-wavelength electrostatic mode, which can heat plasma, for example, through ion Landau damping.

We wish to show in this Letter that nonlinear processes are likely to play an important, if not a dominant, role in the plasma heating processes.

The waves in question here are all primarily electrostatic with the main component of the rf electric field $\vec{E}$ perpendicular to the plasma-confining magnetic field $\vec{B}_0$. At frequencies near the lower hybrid resonance the drift velocity of the ions, $\vec{V}_i \cong e\vec{E}/m_i\omega$, is much smaller than the electron drift $\vec{V}_e \cong c\vec{E}\times\vec{B}_0/B_0^2$. At the power levels used in typical plasma-heating experiments the electron drift velocity near the lower hybrid resonance becomes comparable to, or greater than, the plasma sound speed, so that an instability appears possible. Kindel, Okuda, and Dawson[5] have, in fact, predicted theoretically and observed in numerical simulation experiments a parametric instability which leads to ion and electron heating. They find the threshold drift velocity to be given by

$$\frac{V_e}{V_s} = 4\frac{\omega_p}{\omega_0}\left(\frac{\gamma_L\gamma_H}{\omega_L\omega_H}\right)^{1/2}, \qquad (1)$$

where V_s is the plasma sound speed, ω_p is the frequency of the pump wave, ω_0 is the lower hybrid frequency, and $\gamma_{L,H}$ and $\omega_{L,H}$ are the damping rates and frequencies, respectively, of the low- and high-frequency "daughters" of the decay process.

The low-frequency decay wave is an ion-acoustic mode propagating nearly parallel to the direction of $\vec{V}_e$, and the high-frequency decay wave is similar in nature to the pump wave but has a different frequency and wave number. For the experiments described below $\omega_p \gtrsim \omega_{ip} \approx \omega_0$. If the daughter waves of the decay are weakly damped, the term under the radical in Eq. (1) becomes much less than unity, and the threshold for this process can occur for values of V_e of the order of the sound speed or even smaller.

In an experiment designed to study waves propagating near the lower hybrid-resonance frequency we have discovered a parametric instability with characteristics similar to those described above. A schematic diagram of the experimental arrangement is shown in Fig. 1. Waves are coupled to the plasma with 70-cm-long plates which are driven electrostatically by a balanced rf system. A doubly shielded rf probe travels in the radial direction and is used to detect the plasma oscillations. Not shown is a rotary probe which is capable of moving 360° in the $\hat{\theta}$ direction at a fixed radius in the vicinity of the radial probe. Wavelengths are measured with an amplitude-insensitive rf interferometer. The magnetic field is typically 1000 G, the electron density is approximately 10^{10} cm^{-3}, and the electron tempera-

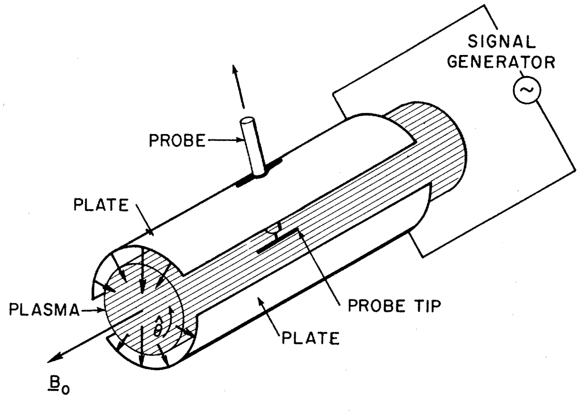

FIG. 1. Schematic of experimental setup. The electrostatic triaxial probe moves radially through a hole in the wave-generating plate. Not shown is a rotary electrostatic probe which can move 360° in the $\hat{\theta}$ direction and a magnetic radially moving probe diametrically opposite the electrostatic probe. The arrows indicate the electric field of the $m = 1$ pump waves.

ture is around 10 eV which is roughly 10 times higher than the ion temperature. The applied frequency is 15 MHz, and the rf power is always less than 100 W. Helium gas is used in these experiments at a pressure ranging up to 4×10^{-3} Torr. The plasma is generated by a helical Lisitano coil or,[6] in some cases, by the wave-generation plates only.

If the applied frequency is near but slightly higher than the maximum value of the lower hybrid frequency in the plasma, waves generated by the plates penetrate radially to the center of the plasma with relatively little attenuation, so that a standing wave pattern is generated in the radial direction.[7] These modes constitute the pump wave in these experiments. They are basically electrostatic oscillations with the main component of electric field in the radial direction and a dispersion relation given very approximately by

$$k_\perp^2 = \frac{m_i}{m_e}\frac{k_\parallel^2\omega_0^2}{\omega^2-\omega_0^2}, \qquad (2)$$

where $k_\perp$ and $k_\parallel$ are the wave numbers perpendicular and parallel to the magnetic field $\vec{B}_0$, and $m_{i,e}$ are the ion and electron masses. The generating plates create an $m = 1$ vacuum electric field, and the driven plasma oscillations are observed to have $m = 1$. Here m is the mode number in the $\hat{\theta}$ direction.

At very low power levels the frequency spectrum of the plasma oscillations consists essentially of a single sharp peak at the pump frequency. At a critical power level, typically around 1 W, a sudden widening of the spectrum occurs on the low-frequency side of the pump-wave frequency (Fig. 2). Very low-frequency oscillations appear simultaneously, and the observed selection rule is $\omega_p = \omega_L + \omega_H$.

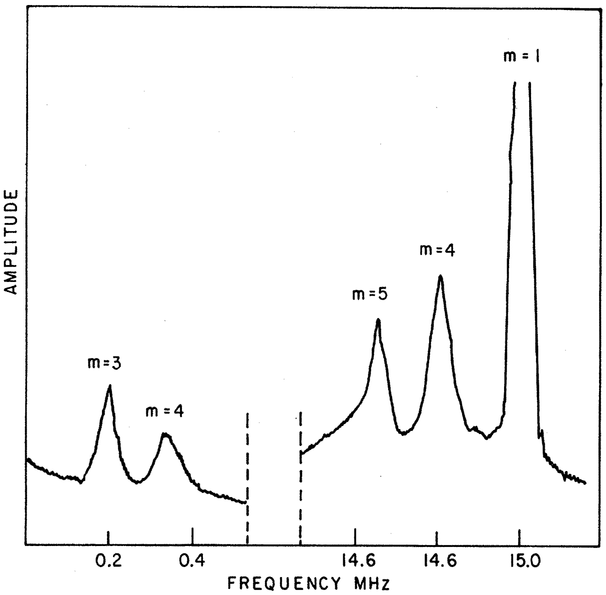

FIG. 2. Frequency spectrum of the pump wave and the decay waves. The m values are the aximuthal mode numbers measured with the rotary probe.

Wavelength measurements of the decay modes show that these waves always propagate in the $\hat{\theta}$ direction, i.e., in the $\vec{E}\times\vec{B}_0$ direction, where $\vec{E}$ is the electric field of the pump wave. The phase velocity of the low-frequency waves equals the plasma sound speed, while the high-frequency decay mode appears to obey the same dispersion relation as the pump wave.

The peaks in the spectrum in Fig. 2 are found to correspond to integral values of the azimuthal mode number m, measurements of which can be made with the rotary probe (Fig. 3). The low- and high-frequency decay waves always differ by unity, the azimuthal mode number of the pump wave. By driving both plates in Fig. 1 in phase instead of 180° out of phase, we are able to generate an $m = 0$ pump wave. In this case the m numbers of the decay waves are observed to be equal. Thus, we see that the angular momentum in this decay process is conserved. We observe that the selection rule for the angular momenta is $m_H = m_p + m_L$ where the m's are all positive integers.

Even though these waves are basically electro-

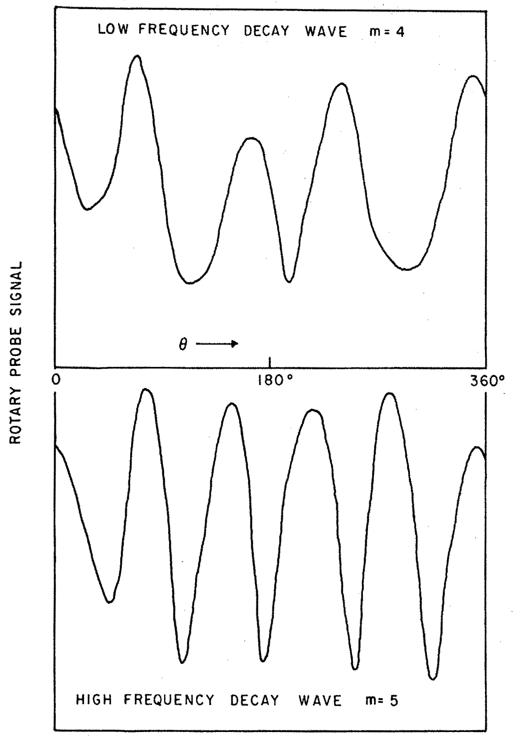

FIG. 3. The sum of the signals from a fixed electrostatic probe used as a reference and the signal from the rotary probe as a function of the angular position of the rotary probe. The *m* values obtained from this technique agree with those obtained with the rf interferometer.

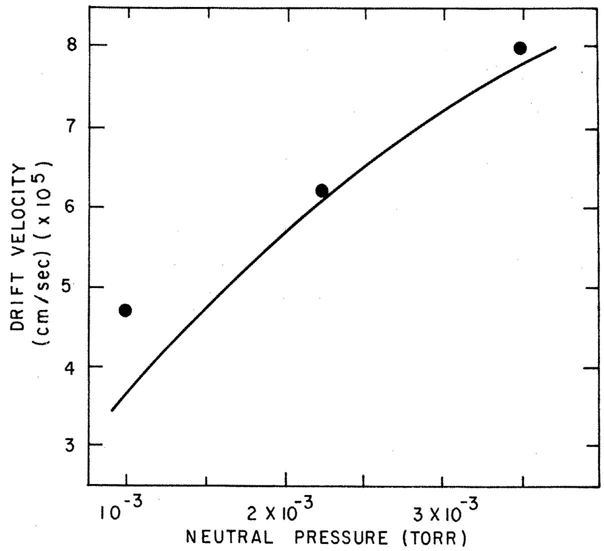

FIG. 4. The observed rf drift velocity as a function of neutral pressure. The solid curve is a plot of Eq. (1) assuming the conditions described in the text. The sound speed for this condition is $\sim 2\times10^6$ cm/sec. The plasma density is the same for each pressure.

static, they do produce currents with corresponding magnetic fields. The main current is that associated with the electron drift and is given by

$$\frac{c}{4\pi}\left(\frac{\partial B_r}{\partial z}-\frac{\partial B_z}{\partial r}\right)=j_\theta=n_e e V_e. \qquad (3)$$

In the geometry used in these experiments the first term on the left-hand side of Eq. (3) is negligible. Therefore, if we can measure $\partial B_z/\partial r$ with a magnetic probe, along with the density, we have a direct measure of the absolute value of the electron-drift velocity.

We have constructed a doubly shielded magnetic probe which is carefully designed to discriminate against electrostatic signals. With this magnetic probe we find that the electron drift velocity at threshold power levels is typically somewhat less than the plasma sound speed. At low densities such that $\omega_p \gg \omega_{ip}$, however, we see that the threshold drift velocity is larger than the sound speed. In Fig. 4 we show the observed threshold velocity as a function of the neutral pressure. The solid curve is a plot of Eq. (1) wherein we assume that the high-frequency waves are damped by electron-neutral collisions and the low-frequency waves by electron-Landau damping parallel to $\vec{B}_0$. The close agreement between the experimental and calculated absolute values is probably fortuitous. Because of the uncertainties in the experimental parameters, we estimate that the expected discrepancy could be as much as a factor of 3.

At power levels an order of magnitude above the threshold level we find a considerable energy content in the decay modes. From measurements of the wave number *k* and the measure of the amplitude of the rf floating potential from the spectrum analyzer, we can compute the energy spectrum and estimate the energy in the high-frequency daughters of the decay relative to the pump-wave energy. We find typically around 10% as much energy in the decay modes as in the pump mode. By careful adjustment of the plasma parameters, however, the integrated energy in the decay in some cases was observed to exceed that in the pump wave by a factor of 2.

Because of the relatively small threshold powers and large saturation amplitudes of the decay waves, we believe this decay instability must be considered in the dynamics of the wave-damping and plasma-heating processes at these frequencies.

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Note added in proof.—It has been called to our attention that M. Porkolab has predicted and calculated the threshold power for the decay of an electron plasma wave into another plasma wave and an ion-acoustic wave.

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Observation of Excitons in a Molecular Liquid: Specular Reflection Spectrum of α-Methylnaphthalene

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The normal-incidence specular-reflection spectrum of liquid α-methylnaphthalene was obtained for the wavelength region from 215 to 400 nm. Comparison of the Kramers-Kronig transform of the reflection spectrum with the absorption spectrum of α-methylnaphthalene is cyclohexane shows the bands of the neat-liquid spectrum shift to lower energy and display significant broadening. These effects support the existence of excitons in molecular liquids.

The existence of excitons in crystalline solids is a consequence of the translational symmetry of the crystal.[1] It has been observed by Rice and co-workers[2] that liquids also have translational symmetry when compared to the thousands of angstroms wavelength of light characteristic of electronic transitions. Thus, it is reasonable to conjecture that exciton states can exist in liquids.

The initial theory of these workers[2a] discussed Wannier excitons in a dense liquid in which an excess electron could be described as a plane wave. It was found that scattering processes could be expected to lead to broadening of the exciton states. Later the theory for excitons in liquids was developed[2b] along the lines of the Fano model of polarization waves in a simple lattice. The structure of the liquid appears explicitly in this construct. An approximate form of this theory,[2c] which is more applicable to Frenkel excitons, uses a Drude-type model to describe the electronic states; nevertheless, the theory has not been applied to any molecular liquid. However, it is possible to understand qualitatively what may be expected if excitons do exist in molecular liquids. Two main features should be apparent. The primary one is a broadening of bands because the lifetimes of the electronic excitations will be approximately one tenth the lifetime for typical thermal excitations. The set of exciton levels in the liquid would be expected to appear as an unresolved or poorly resolved spectrum. Secondly, a shift in frequency from that of the solution or vapor spectrum may be expected. While excitons in atomic liquids have been detected,[3] molecular liquids have not been investigated.

In an effort to observe excitons in molecular liquids, α-methylnaphthalene was studied in the wavelength region from 215 to 400 nm. Normal-incidence specular-reflection spectra were obtained on samples of the neat liquid using a reflectometer described previously.[4] The light beam was directly incident on the surface of the liquid which was contained in a small glass boat. This eliminates problems of refractive index