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EXCITATION OF PSEUDOWAVES IN A PLASMA VIA A GRID*

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When a time-varying potential is placed on a grid located in a plasma, coherent bursts of charged particles having peak energies corresponding to the applied potential are emitted from the grid region. These ion bursts produce an ion-wavelike phenomenon, which is not predicted by the ordinary dispersion relation. We have observed these "pseudowaves" having wavelengths larger than the Debye radius, which suggests that in this case some cooperative electrostatic process must be present. These pseudo ion waves have been used as a tool to study plasma phenomena.

Recently, while doing dispersion experiments with ion-acoustic waves in rare-gas discharge plasmas,[1,2] we discovered a new wavelike phenomenon which is not predicted by the usual dispersion relation. A similar discovery has just been reported for a cesium plasma.[3] The purpose of this Letter is to report some unusual properties of these so-called pseudowaves. These pseudowaves appear to be coherent bursts of energetic ions originating at our gridded transmitter and striking our ion-sensitive detector. Since the wavelength of these pseudowaves can be larger than the Debye radius, some new, cooperative wave motion possibly is present.

The measurements are made in a spherical gas-discharge-tube plasma some 20 cm in diameter, which was used in our ion-acoustic wave work.[2] This plasma, which is characterized by its quiescent behavior, is generated by ionizing collisions between a diffuse spray of energetic electrons from an electron gun and the background gas. Using pressures on the order of 1 μ, we generate rare-gas plasmas having densities from 10^8 to 10^9 cm^{-3} and electron temperatures of 1-2 eV. Both pseudowaves and ion-acoustic waves are propagated between movable, negatively biased electrodes located in the plasma. Both types of waves are generated by placing a time-varying potential on the transmitter electrode. Empirically, we find if we use a solid flat disc as a transmitter—as in all our early ion-acoustic-wave work—then pseudowaves are never observed. Pseudowaves are always observed, however, if gridded transmitters are used. The negatively biased detector is connected to ground through a small resistor and draws a small ion current from the surrounding ion sheath, thus being sensitive to small fluctuations in ion density in the sheath region.

Figure 1 shows schematically how we think pseudowaves are generated when a transient negative potential is placed on a gridded transmitter probe. When the potential well is present, ions will be accelerated toward the grid. An ion reaching the plane of the grid will have acquired the full potential of the applied voltage and will have a velocity given approximately by the formula shown, where V is the amplitude of the ap-

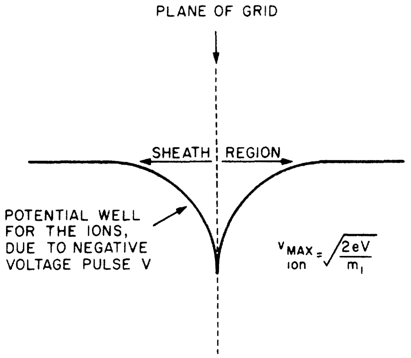
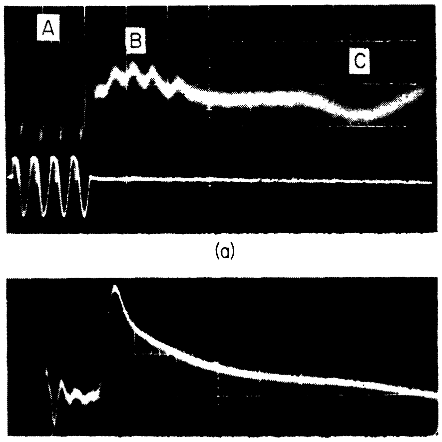


FIG. 1. Model for generation of pseudowaves by application of a transient negative potential to a gridded probe in a plasma.

plied voltage. If the negative potential is quickly removed just at the time such an ion reaches the grid, then the ion will continue on through the grid and out into the plasma with its full acquired velocity. Such an ion striking the detector will produce a signal which is indistinguishable from that of an ion striking the detector due to ion-acoustic-wave motion. This model obviously predicts that the velocity of pseudowaves should depend upon the amplitude of the exciting voltage. This behavior contrasts to that for ion-acoustic waves, for which the velocity is independent of exciting-voltage amplitude. Since this model obviously requires that the accelerated ions be able to pass through the grid plane, pseudowaves should be observed only when gridded transmitters are used. The model also predicts that a pseudowave will not be generated until the negative potential is removed. This is observed experimentally and contrasts to ion-acoustic-wave excitation, which occurs both at the onset of the applied potential and at its removal.



(a)

(b)

FIG. 2. (a) Detection of pseudowaves and ion-acoustic waves, generated simultaneously by sine-wave trains applied to a negatively biased gridded transmitter. The lower trace shows the exciting signal, the frequency of which was above the ion-plasma frequency. The upper trace shows the received signal, consisting of three parts: *A* is a directly coupled electrostatic signal; *B* is the pseudowave signal, due to bursts of ions accelerated toward the receiver from the backside of the transmitter; and *C* is the slow-moving ion-acoustic-wave signal. Note that *B* shows little dispersion for this excitation characterized by a higher-than-ion-plasma frequency. Also note that *B* has a very low-frequency component present. The time scale is 10 μsec per large division, the vertical scale for the lower trace is 20 V per large division, and the transmitter-receiver spacing was ~ 7.5 cm. (b) A pseudowave excited by a delta function. Note the fast rise time and the long tail of the received signal. Here the wave extends over at least 100 Debye radii: $n_e \sim 10^8\ \text{cm}^{-3}$; $T_e \sim 1$ eV; $\lambda_{\text{Debye}} \sim 0.7$ mm; $\lambda_{\text{wave}} \sim 10$ cm. Transmitter-receiver spacing ~ 3 cm; measured pseudowave velocity $\sim 7 \times 10^5$ cm/sec; time scale $= 2$ μsec per large division; delta function ~ 1 μsec wide and -45 V high. Both (a) and (b) were obtained using a xenon plasma.

Figure 2(a) shows the detection of both pseudowave and ion-acoustic-wave signals, both waves being generated simultaneously by the same bursts of sine waves placed on the transmitter electrode. The lower trace shows the exciting signal on the transmitter while the upper trace shows the signals received by the detector. The received signal consists of three parts: (1) a directly coupled electrostatic signal labeled *A*, (2) a rapidly propagating pseudowave signal labeled *B*, and (3) a slowly propagating ion-acoustic-wave signal labeled *C*. For this particular case, the exciting frequency was above the ion-plasma frequency. Note that the ion-acoustic-wave signal has been distorted by dispersion and Landau damping,[1] while the pseudowave signal seems relatively unaffected by the excitation at a frequency higher than ion-plasma frequency. This represents a second important differentiating characteristic between pseudowaves and ordinary ion-acoustic waves. Although not demonstrated by the data shown, the observation was made that whereas ion-acoustic waves suffer severe damping in the vicinity of the ion-plasma frequency due to dispersion and subsequent Landau damping,[1,4] the damping rate for pseudowaves remains relatively constant in this frequency range. Note that the sine-wave burst in the pseudowave is superimposed on a low-frequency bump that corresponds to a wavelength having a frequency less than the ion-plasma frequency. For delta-function excitation, such as shown in Fig. 2(b), pseudowaves having very large wavelengths have been observed. For these long wavelengths there presumably must be some sort of cooperative effort present. The simultaneously excited ion-acoustic wave is not seen in Fig. 2(b) because it appeared much later in time. A fourth important difference between the two phenomena is seen if propagation is carried out in a two-ion-species plasma. For this case, in agreement with theory, we see only one ion-acoustic wave, whose velocity is intermediate between that expected for the two separate ion species.[5] We see two pseudowaves, however, one corresponding to each of the two ion masses present.

Above, it was pointed out that the velocity of pseudowaves should and does depend on the amplitude of the exciting voltage. Figure 3 shows some typical data illustrating this dependence. On the vertical axis is plotted the measured pseudowave velocity while the exciting-voltage amplitude is plotted on the horizontal axis. For these measurements the exciting signals were square-wave voltage pulses of varying amplitude. The superimposed straight line shows both quantitatively and qualitatively the velocity expected for a $(2eV/m_i)^{1/2}$ dependence. At low voltages, the agreement between experiment and theory is good; at the larger amplitude pulses, however, the measured velocity is appreciably smaller than that predicted by the simple equation. We think the observed discrepancy is explained by the finite fall time of our square-wave pulses. If the exciting voltage does not fall instantaneously to zero, an ion leaving the grid will feel a retarding potential and will lose some of its energy. Experimentally, we find that, indeed, the fall time for our larger amplitude pulses is becoming quite appreciable when compared with the transit time of the ions through the grid-sheath region. The voltage range used here is the same as that normally used in our ion-acoustic-wave studies. Future work will include using smaller voltages, for which the pseudowave properties may well be different.

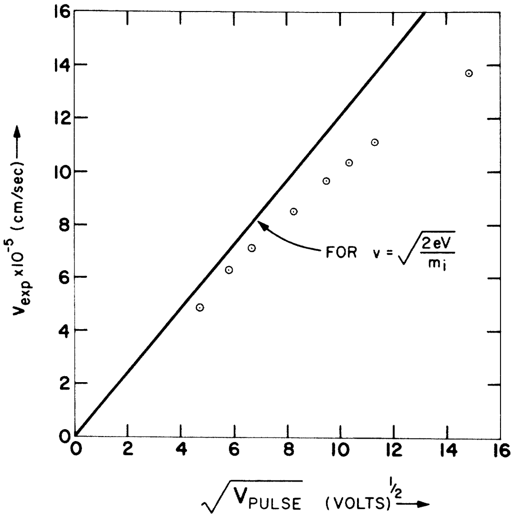


FIG. 3. Dependence of pseudowave velocity on exciting voltage amplitude. Square-wave pulses of varying amplitude were used. The straight line shows the velocities that would be expected for a $(2eV/m_i)^{1/2}$ dependence. The measurements were made in a xenon plasma.

We have looked at the damping of pseudowaves as a function of propagation distance, and find, typically, e-folding damping distances on the order of 1-3 cm. Qualitatively, the pseudowave damping distance varies in the same way with exciting voltage amplitude as does the pseudowave velocity. Or, in other words, the mean free path of a pseudowave ion is directly proportional to the velocity of the ion. Using our pseudowave damping data, we can calculate σ, the microscopic cross section for ion scattering by neutrals. To first order, we find that σ, which, at these speeds, is due primarily to resonant charge exchange, is given (in cm^2) approximately by 1×10^{-8} divided by the ion speed (in cm/sec). This is in reasonable agreement with data found in the literature.[6-8]

To conclude and summarize: We have discovered and made preliminary studies of a new wavelike phenomena which can occur under conditions which have been used in the study of ion-acoustic waves and other phenomena. We anticipate that these pseudowaves will be useful in studying plasma phenomena. Our scattering cross-section measurements for low-energy ions were fast, easy, and accurate. Another possible application is to study the electric fields present in sheaths. Finally, since these pseudowaves have been observed with wavelengths large compared with the Debye radius, a new wavelike process in plasmas may have been observed. It has been suggested[9] that these are similar to the Van Kampen modes.[10]

We appreciate the help and encouragement of Professor David Montgomery, of the University

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ZERO SOUND IN CLASSICAL LIQUIDS*

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Starting from a zero-sound approach, a calculation of the spectral function of the current-current correlation, which is valid at short wavelengths and high frequencies, is given for classical liquids. The theory is used to explain results of neutron inelastic scattering in liquid argon.

Recently, Pines[1] has advanced arguments for the existence of a zero-sound mode in liquid He^3 and He^4 over a wide temperature range—a range in which neither Landau's theory of Fermi liquids is applicable (for He^3) nor He^4 is a superfluid. These considerations led Pines to conjecture that a zero-sound mode at short wavelengths and high excitation frequencies might be a quite general liquid property. This suggestion of Pines has hitherto not been investigated in any quantitative manner for the case of classical liquids. Rather, experimentalists have used phenomenological models[2,3] to explain neutron inelastic scattering results.

The purpose of this Letter is twofold: (i) to present experimental data for the spectral function of the current-current correlation function in liquid argon, and (ii) to develop a theory based on Pines' suggestion and compare its consequences with experiment. The theory is reasonably successful and opens up the possibility for further applications.

In contrast to the hydrodynamic case, the restoring force responsible for the zero-sound mode is the average self-consistent field of all the particles acting in concert, as for plasmons in an electron liquid. The average polarization potential corresponding to this restoring force is defined by

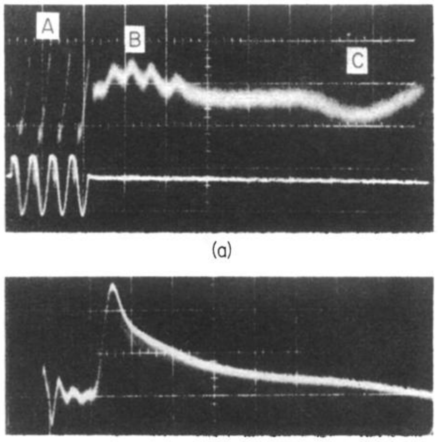
$$\varphi_{\mathrm{pol}}(\vec{q},\omega)=\psi(\vec{q})\langle\rho(\vec{q},\omega)\rangle, \tag{1}$$

where $\psi(\vec{q})$ is to be determined later and $\langle\rho(\vec{q},\omega)\rangle$ is the Fourier transform of the average fluctuation in the particle density. The density-density response function is given by[1]

$$\chi(\vec{q},\omega)=\frac{\chi_{sc}(\vec{q},\omega)}{1-\psi(\vec{q})\chi_{sc}(\vec{q},\omega)}. \tag{2}$$

Here $\chi_{sc}(\vec{q},\omega)$ is a measure of the response to both the external and the polarization field. The problem is to determine $\chi_{sc}(\vec{q},\omega)$ and $\psi(\vec{q})$.

We make the physical assumption that $\chi_{sc}(\vec{q},\omega)$ is determined by the single-particle motion. As



(a)

(b)

FIG. 2. (a) Detection of pseudowaves and ion-acoustic waves, generated simultaneously by sine-wave trains applied to a negatively biased gridded transmitter. The lower trace shows the exciting signal, the frequency of which was above the ion-plasma frequency. The upper trace shows the received signal, consisting of three parts: *A* is a directly coupled electrostatic signal; *B* is the pseudowave signal, due to bursts of ions accelerated toward the receiver from the backside of the transmitter; and *C* is the slow-moving ion-acoustic-wave signal. Note that *B* shows little dispersion for this excitation characterized by a higher-than-ion-plasma frequency. Also note that *B* has a very low-frequency component present. The time scale is 10 μsec per large division, the vertical scale for the lower trace is 20 V per large division, and the transmitter-receiver spacing was ~7.5 cm. (b) A pseudowave excited by a delta function. Note the fast rise time and the long tail of the received signal. Here the wave extends over at least 100 Debye radii: $n_e \sim 10^8$ cm^{-3}; $T_e \sim 1$ eV; $\lambda_{\text{Debye}} \sim 0.7$ mm; $\lambda_{\text{wave}} \sim 10$ cm. Transmitter-receiver spacing ~3 cm; measured pseudowave velocity $\sim 7 \times 10^5$ cm/sec; time scale $= 2$ μsec per large division; delta function ~1 μsec wide and -45 V high. Both (a) and (b) were obtained using a xenon plasma.