# Propagation of argon- and helium-ion acoustic modes in an argon-helium plasma

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(Received 1 June 1976)

Linear, nondispersive ion acoustic wave propagation in an argon-helium plasma is investigated in a double plasma device. The experimental wave patterns show that there exists a range of light ion concentration $\alpha$ where both argon and helium modes can be excited and propagate simultaneously, contrary to a previously published experiment of Nakamura *et al.* The phase velocity of the mode is only slightly affected by the presence of He ions. In the case of the He wave, it can be described by a reduced mass $M_r = M_{Ar}/[1-\alpha+\alpha(M_{Ar}/M_{He})]$, showing that the He and Ar ions follow an adiabatic equation of state. The observed increase in Landau damping of the Ar mode is related to the He resonant ions, whereas the damping of the He mode is mainly due to the reduction in the phase velocity of the wave.

## I. INTRODUCTION

Although in fusion research as well as in basic plasma physics, one often tries to work with plasma containing only one ion species, two-species plasmas present new interesting properties. In connection with the plasma heating problem, Kaw and Lee,[1] Ott *et al.*,[2] and Harms *et al.*[3] studied theoretically the parametric decay of lower hybrid[1,2] or magnetoacoustic waves[3] in a plasma with two ion species. Experimentally, light ions in a heavy-ion plasma have been used for different purpose: the He ions have been added into an argon plasma to study the increase of the threshold of parametric decay of a Langmuir wave[4] or, in a different domain, to induce turbulence in a collisionless shock wave.[5] Multi-ion plasmas are also relevant to space physics since a wide variety of ions exists in the ionosphere.

It is therefore important to study precisely the wave properties in a two-ion-species plasma. The most simple and basic wave which includes ion dynamics is the acoustic wave. This problem was first considered by Fried *et al.*,[6] who computed the dispersion function in a two-ion-species plasma. The two major results of their calculations, which will be discussed in more detail in the next paragraph, are the following: below a certain temperature ratio $\theta = T_e/T_i$ ($\theta \leq 20$) the dispersion relation presents two branches, which we shall identify as the Ar and He branches when dealing with an Ar-He plasma. Secondly, the presence of second ion species will modify the damping rate due to a modification of the number of resonant ions.

The damping variation has been investigated by several authors. Hirose *et al.*[7] introduced a small amount of the ions into a Xe plasma (density ratio of He to Xe ions $\simeq$1%) and observed an increase of Landau damping. Using a temperature ratio $\theta = 16$, they found good agreement between the theoretical value and experiment. A systematic study of the influence of light ions in a heavy-ion plasma has been made by Tran and Coquerand[8] and Nakamura *et al.*[9] These authors have varied the He concentration $\alpha$ ($\alpha$ = light ion density/plasma density) between 0% and 100% and measured the phase velocity and damping rate of linear, nondispersive acoustic waves propagating in a large unmagnetized plasma. In Ref. 9, the temperature ratio $\theta$ was greater than 20 ($\theta \approx 25$), and a smooth change of the phase velocity $\omega/k_r$ and the damping rate $k_i/k_r$ from their values in a pure-Ar plasma to the ones in a pure-He plasma was observed: only one acoustic mode exists in a two-component plasma with $\theta = 21, 25$. Both $\omega/k_r$ and $k_i/k_r$ agree with the theory of Fried *et al.*[6] if one takes into account collisional damping for $\alpha$ greater than 40%. The experiment of Tran and Coquerand has been conducted in a collisionless plasma with smaller temperature ratio ($\theta = 9$). Their preliminary results[8] show a discrepancy with the work of Nakamura *et al.*[9] For increasing $\alpha$ the Ar branch does not change smoothly to the He one, but interference patterns are observed in a given $\alpha$ range indicating the simultaneous presence of the two modes.

In this paper we would like to present detailed measurements showing clearly for the first time the existence of the two acoustic modes in a two-component plasma. A theoretical review of the properties of the dispersion relation is presented in Sec. II. Section III is devoted to the experimental apparatus. Results are discussed in Sec. IV.

## II. DISPERSION RELATION

We consider a two-ion-species (He-Ar) plasma. The electrons are isothermal with temperature

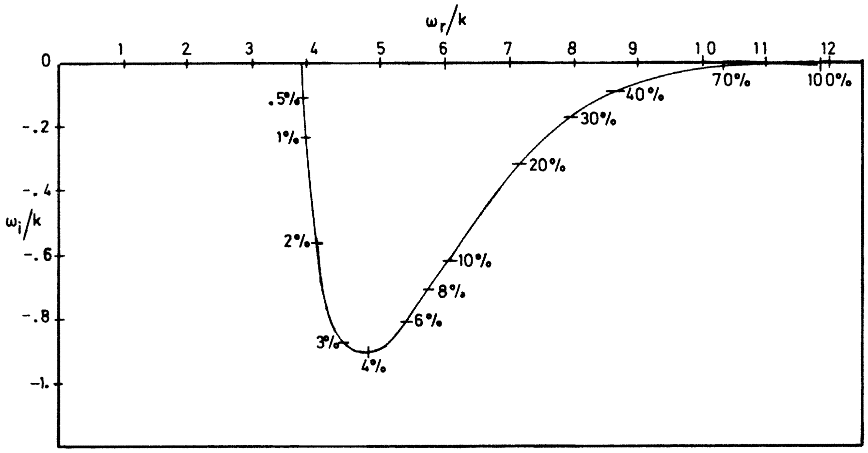


FIG. 1. $k=0$ limit of the dispersion relation in argon-helium plasma. The temperature ratio $T_e/T_i$ is 25. Horizontal bars on the curves indicate the light-ion concentration.

$T_e$ and the two ion species have a Maxwellian distribution with equal temperature $T_i$. The dielectric function for low-frequency longitudinal wave is given by

$$\epsilon(\omega,k)=1+\frac{1}{k^2\theta}-\frac{1}{2k^2}\left[(1-\alpha)Z'\left(\frac{\omega}{k}\right)+\alpha Z'\left(\frac{\omega\mu^{-1/2}}{k}\right)\right]. \tag{1}$$

$Z$ is the plasma dispersion function, $\theta$ the temperature ratio, and $\mu$ the Ar-to-He mass ratio. We have normalized $k$ to $(n_0e^2/\epsilon_0T_i)^{1/2}$, $\omega/k$ to $(2T_i/M_{\rm Ar})^{1/2}$, and $\omega$ to $(2n_0e^2/\epsilon_0M_{\rm Ar})^{1/2}$. The equation $\epsilon(\omega,k)=0$ yields the dispersion relation for ion waves and has been solved numerically for various $\theta$.

For $\theta=25$, the real part of $\omega/k$ increases with increasing $\alpha$ and changes smoothly from the value $[(\theta+3)/2]^{1/2}$ for $\alpha=0\%$ to $[\mu(\theta+3)/2]^{1/2}$ for $\alpha=100\%$ (Fig. 1). The damping rate at first increases for $\alpha$ up to 4% due to resonant He ions. Above this value of $\alpha$, the velocity becomes larger so that less and less Ar and He ions are resonant. Approximate expression for the phase velocity and damping rate can be found from the asymptotic expression of the $Z$ function:

$$\frac{\omega_r}{k}=\left(\frac{\theta(1-\alpha+\alpha\mu)}{2}+\frac{1.5(1-\alpha+\alpha\mu^2)}{1-\alpha+\alpha\mu}\right)^{1/2}, \tag{2}$$

$$\frac{\omega_i}{\omega_r}=\left(\frac{\pi(1-\alpha+\alpha\mu)}{8}\right)^{1/2}\times\left[\left(\frac{m_e}{M_{\rm Ar}}\right)^{1/2}+\frac{\alpha\theta^{3/2}}{\mu^{1/2}}\exp\left(-\frac{\omega_r^2}{k^2\mu}\right)+(1-\alpha)\theta^{3/2}\exp\left(-\frac{\omega_r^2}{k^2}\right)\right]. \tag{3}$$

Equations (2) and (3) give the well-known result for the phase velocity and damping rate in the limits $\alpha=0\%$ and $\alpha=100\%$.[10] However, they are only valid for $\alpha<1\%$ and $\alpha>20\%$ since for intermediate value of $\alpha$, the imaginary part of the dispersion equation cannot be neglected.

For lower $\theta$, the solutions of the equation $\epsilon(\omega,k)=0$ give a new result (Fig. 2). Equation (1) admits now two low-frequency roots which

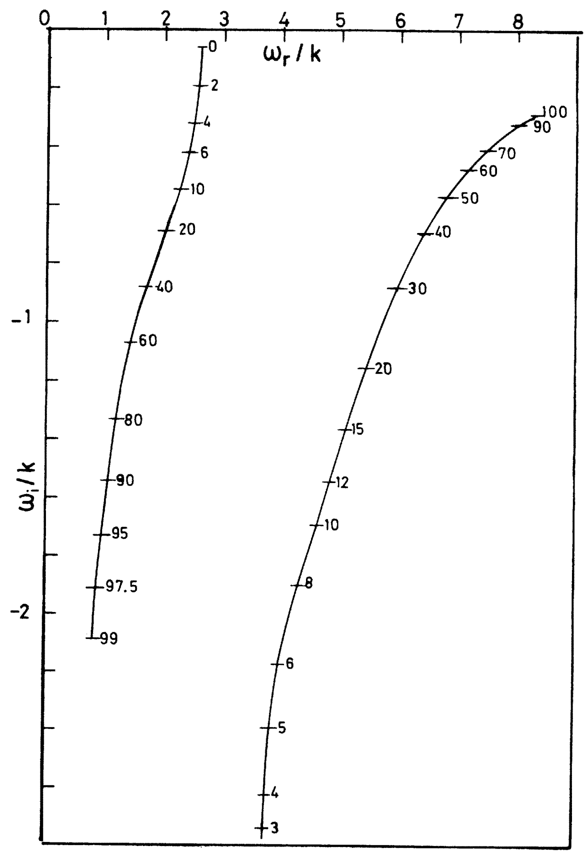


FIG. 2. $k=0$ limit of the dispersion relation of the argon and helium principal modes. The temperature ratio is 10. Horizontal bars on the curves indicate the light-ion concentration.

will be called the Ar and He principal modes. These modes can be considered as modifications of the pure-Ar (He) mode due to the presence of the He (Ar) ions. As $\alpha$ is varied, these two modes never cross in the complex $\omega/k$ plane, and one would expect to observe them both, specially for $10\% < \alpha < 30\%$, where their damping rates are not too different. The damping rate of the Ar mode (He mode) is increased (decreased) as $\alpha$ increases. The physical reason of these effects will be discussed later in connection with experimental results. Finally, one notes that Eqs. (2) and (3) are relatively good approximations of the He branch for $\alpha > 40\%$. Below this range and for the whole Ar branch (except at $\alpha = 0\%$) the damping rate is too important and asymptotic expansion of the $Z$ function cannot be applied.

## III. EXPERIMENTAL SETUP

Measurements have been made in a multipole double plasma (DP) device[11] which has been described elsewhere.[8,12] At typical conditions (base pressure $p_0 = 2.10^{-7}$ Torr, gas pressure $= 10^{-4}$ Torr, emission current $= 400$ mA) the plasma density is about $10^9$ cm$^{-3}$ with $T_e = 1$ eV. The ion temperature $T_i$ in a pure-gas plasma was deduced from the damping rate of the ion wave and was found to be about 0.11 eV; the temperature ratio is 9 and is much smaller than in the experiment of Nakamura *et al.*[9] in which the temperature ratio was 25. In this plasma one can reasonably assume that $T_i$ does not vary and is equal for both Ar and He ions: the ion energy equipartition time is 60 $\mu$sec, whereas the plasma confinement time is as high as 200 $\mu$sec.[8]

While working with a two-component plasma, the He and Ar neutral gases were introduced one after the other using two different inlets. This procedure allows us to measure the partial pressure of each gas. From the plasma density versus neutral pressure dependency of pure He and Ar, one can then compute the light-ion concentration. We estimate the precision on the determination of $\alpha$ to be $\pm 5\%$. The validity of our method rests on the assumption that, in presence of a mixture, the ionization rate and the confinement time of Ar and He ions are not affected by the other species. Density measurements in pure He and Ar at a given pressure and in a mixture containing the same partial pressure of these gases have confirmed this assumption.

Low-frequency waves have been launched by applying a small sinusoidal voltage on the driver chamber. To avoid any ion beam which may modify the phase velocity and damping rate of the wave, the potentials of the driver and target plasma have been carefully adjusted by comparing the wavelength of an ion wave propagating in the driver and target plasma. The applied signal ($V = 50$–$100$ mV) is a sinusoid ($\nu = 100$–$400$ kHz) the amplitude of which is modulated by a low-frequency ($\nu = 5$ kHz) voltage driven from the reference channel of a lock-in amplifier (PAR-126). The output signal from a moving Langmuir probe collecting ion saturation is mixed with the high-frequency signal and the output of the mixer is fed into the lock-in. The wave pattern is recorded directly on a X-Y recorder or on a punched paper tape. In the latter case, the probe position and the lock-in output are digitized using two precision analog-to-digital converters. An opto-electronic device connected with the probe motion mechanism allows us to sample the wave pattern at every 0.25 mm. These digital data are then Fourier transformed to yield the wave number $k_r$ and damping factor $k_i/k_r$.

## IV. EXPERIMENTAL RESULTS

Although in our measurements the ion plasma frequency $\nu_{pi}$ varies as $\alpha$ changes, the wave frequency is always small compared to $\nu_{pi}$ ($\nu/\nu_{pi} < 0.3$). The measured phase velocity and damping rate were also found to be independent of $\nu$, showing that our results could be described by the $k=0$ limit of the collisionless dispersion relation.

While looking at the wave pattern (Fig. 3), one immediately remarks that for an intermediate

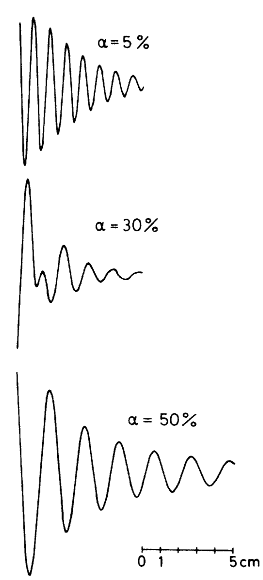


FIG. 3. Typical experimental wave patterns for different concentration $\alpha$ ($\alpha = 5\%$, 30%, and 50%). The frequency of the wave $\nu$ is 200 kHz. Note the pattern observed at $\alpha = 30\%$, which is due to the interference of the He and Ar waves propagating simultaneously.

range of $\alpha$ ($10\% < \alpha < 30\%$) the wave form is not a damped sinusoid but results from the superposition of two damped sinusoidal waves. Similar results are also obtained when the separation grid of the DP device is used as an exciter instead of the DP mechanism. In this range of $\alpha$ the Fourier spectrum of the experimental structure presents two peaks. As shown in Fig. 4, the measured phase velocity and damping rate agree with the computed values. The two modes we have observed can therefore be identified as the Ar and He principal modes whose existence has been predicted by the theory of Fried *et al.*[6] Outside this $\alpha$ range ($10\% < \alpha < 30\%$) only the Ar mode ($\alpha < 10\%$) or the He mode ($\alpha > 30\%$) has been detected; the He (or Ar) mode becomes too heavily damped to be a normal mode of the plasma, and it should be considered as a quasimode. Moreover as $\alpha$ increases, the amplitude of the Ar mode decreases and finally disappears.

For $\alpha < 10\%$, the wave form is a damped sinusoid (Fig. 3). Its phase velocity is nearly independent of $\alpha$ (Fig. 5), and its damping rate $k_i/k_r$ increases with $\alpha$ due to resonant He ions (Fig. 6); for $\theta = 10$, the normalized phase velocity $\omega/k_r$ is 2.5, whereas the normalized He thermal velocity ($\mu^{1/2}$) is 3.2 a value very close to $\omega/k_r$. The Landau damping is therefore mainly due to He ions.

Finally for $\alpha > 30\%$, where only the He mode propagates, the phase velocity increases with increasing $\alpha$ since the reduced mass $M = M_{Ar}/(1 - \alpha + \alpha\mu)$ tends toward $M_{He}$ (Fig. 5). Consequently the damping rate $k_i/k_r$ decreases for increasing $\alpha$ as there are less and less resonant Ar and He ions.

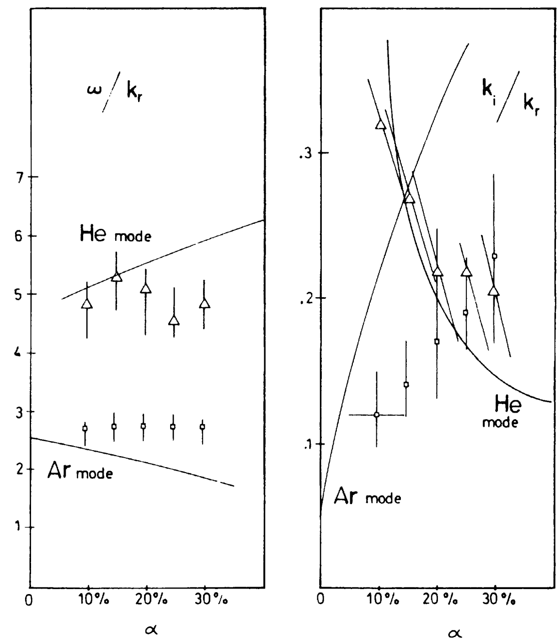


FIG. 4. Measured phase velocity $\omega/k_r$ and damping rate $k_i/k_r$ for $10\% < \alpha \lesssim 30\%$. In this concentration range, the experimental wave pattern are due to the interference of the Ar and He modes whose characteristics are presented in the figure. $\omega/k_r$ is normalized to $(2T_i/M_{Ar})^{1/2}$.

In their previous study of the influence of He ions in an Ar plasma with $\theta = 25$, Nakamura *et al.*[9] reported only one wave propagating in the plasma; as shown in Figs. 5 and 6. The discrepancy be-

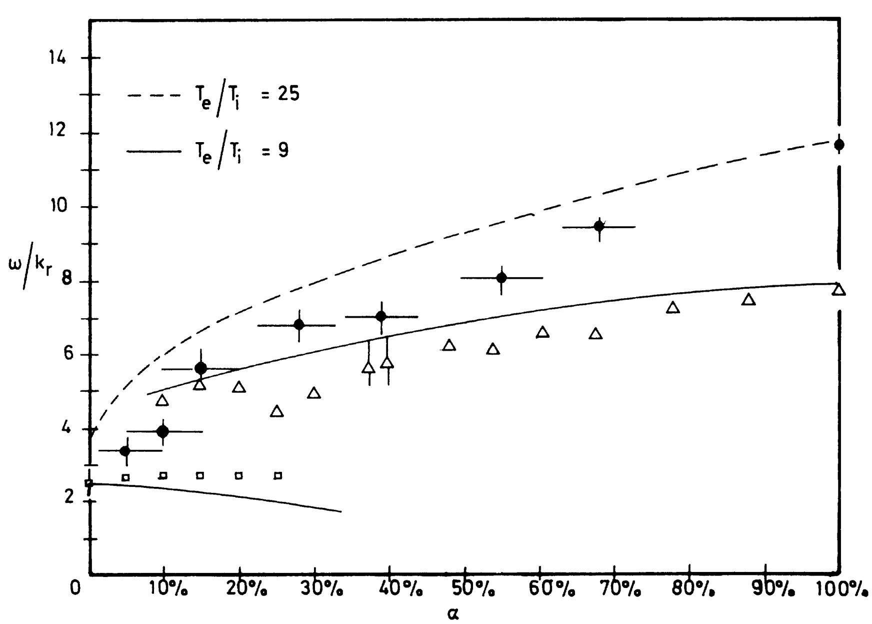


FIG. 5. Measured phase velocity $\omega/k_r$ in dependence of $\alpha$ for two different $T_e/T_i$. The solid lines are computed from Eq. (1) using $\theta = 9$, and the dashed line using $\theta = 25$. △ are the measured values for the He mode and □ for the Ar mode. ● are values obtained by Nakamura *et al.* (Ref. 9) in a plasma with $\theta = 25$.

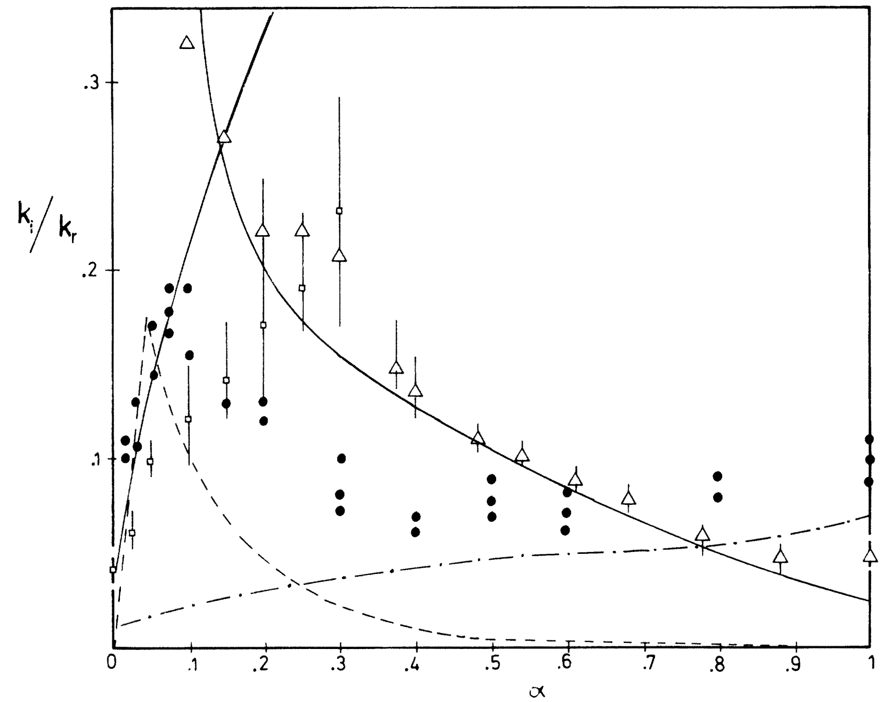


FIG. 6. Experimental damping rate as a function of the light-ion concentration. The solid lines are the theoretical curves for $\theta = 9$, and the dashed lines are obtained for $\theta = 25$. △ correspond to the He mode and □ to the Ar mode. ● are values obtained by Nakamura *et al.* (Ref. 9) for $\nu = 400$ kHz. Note that the Nakamura *et al.* (Ref. 9) results are much above the theoretical curve (- - -) which has been computed for a collisionless dispersion relation. However, their results agree much better if collisional damping is taken into account (curve —·—·—).

tween their work and our results is related to the difference in temperature ratio $\theta$. As we have pointed out in Sec. II, in the limit $k \to 0$, the dispersion relation admits only one branch for $\theta = 25$ (Fig. 1). On the contrary, for lower $\theta$ (for example $\theta = 9$ as in our experiment) the Ar and He modes remain distinct for all value of $\alpha$. In a recent report[13] which the authors received after submitting the present work, Nakamura *et al.* have also observed the two modes in a plasma with $\theta = 10$, confirming our results. Finally, we have not observed any collisional damping as has been reported in Ref. 9.

## V. CONCLUSION

Our experimental work has shown for the first time the clear existence of the two ion acoustic prinicpal modes as predicted by Fried *et al.*[6] The possibility of observing their simultaneous propagation is critically connected to the temperature ratio $\theta = T_e/T_i$. If $\theta$ is too high (e.g., $\theta = 25$) the Ar mode changes smoothly to the He one.[9] For lower $\theta$ ($\theta \lesssim 20$) they are always distinct and have been observed simultaneously.

From the propagation characteristics of ion waves, it appears that they can be used as a diagnostic tool for determining $\alpha$ in a two-ion-species plasma. Since the damping rate and the phase velocity depend strongly on $\alpha$, a measurement of these quantities is, in principle, sufficient for determining $\alpha$ provided $T_e$ or $T_i$ is known. Such a diagnostic seems to be easier, though much less precise, than a direct mass-spectrometer measurement.

## ACKNOWLEDGMENTS

The authors are grateful to Professor E. S. Weibel, Dr. M. Bitter, and Dr. R. W. Means for helpful discussions. The technical assistance of H. Ripper and J. P. Perotti was greatly appreciated. This work was supported by the Swiss National Science Foundation.


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