Laser Scattering Measurements of Thermal Ion-Acoustic Fluctuations in Collisional Plasmas

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The thermal ion-acoustic fluctuation spectrum of a high-density, low-temperature (2 eV, 10^{17} cm^{-3}), collisional plasma was measured in a CO$_2$-laser scattering experiment. The measured spectra differed substantially from spectra observed in collisionless plasmas. Fluctuations at the ion-acoustic frequency were strongly enhanced and the width of the resonance was significantly narrowed in comparison to the collisionless case. The Bhatnagar-Gross-Krook theory proved most successful in describing the data.

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The relative importance of collisional and collective interactions in plasmas is characterized by the plasma parameter $g=1/n\lambda_D^3$, which measures the ratio of the mean interparticle potential energy to the mean plasma kinetic energy. For most plasmas produced in the laboratory or found in astronomical sources, g is small and the effects of collisions are not important. As a consequence, most of the kinetic theory that has been developed to model the behavior of plasmas depends on expansions in g and does not specifically consider collisional effects. There are, however, some plasmas, such as the ones found in the interior of stars, in laser fusion experiments, and in dense, low-temperature arcs, that are strongly influenced by collisions and for which g is no longer small. As a result, the standard collisionless theories are inadequate in treating such plasmas. Efforts to generalize the theory have been made by several authors[1-5]; however, these theories differ in their predictions and current experimental data[6-8] are insufficiently precise to test their validity.

In this Letter we present laser scattering measurements of thermal ion-acoustic fluctuation spectra from dense, low-temperature ($n_e \sim 10^{17}$ cm^{-3}, $T_e \sim 2$ eV , $n\lambda_D^3 \sim 3.5$), i.e., collisional, helium and argon plasmas which are used to test the theoretical predictions in the collisional regime. As a complement to the scattering measurements, the plasmas were also fully diagnosed by independent spectroscopic, interferometric, and probe measurements, in order that comparison to theory could be made without resorting to parameter fitting schemes.

Ion-acoustic fluctuations were selected because of their high sensitivity to the effects of collisions, given their relatively low frequency. In particular, the degree to which the scattering spectra can be expected to be altered by the presence of collisions is determined by the ratio (ν_{ii}/kC_s) of the ion-ion collision frequency ν_{ii} to the ion-acoustic fluctuation frequency kC_s [where $k=4\pi/\lambda_0 \sin\theta/2$ is the fluctuation wave number and $C_s=(\gamma kT/m_i)^{1/2}$ is the ion-acoustic velocity]. If $\nu_{ii}/kC_s \gtrsim 1$, collisional effects are important and for given plasma conditions they can be maximized by a choice of small wave numbers. In this work collisional effects were maximized by the use of a long-wavelength ($\lambda_0=10.6$ μm) CO$_2$ laser and small scattering angles (4°–9°). This choice of scattering parameters was, in fact, ideally suited to test the validity of the various theories, since in this parameter regime the predicted ion-acoustic fluctuation spectra vary substantially from theory to theory, as is demonstrated in the calculations presented in Fig. 1.

The plasmas used in this experiment were generated with a small pulsed arc that was energized by a 1200-μF capacitor bank charged to 1–2 kV. In normal operation, the arc was filled with 1–7 Torr of helium or argon gas and discharge currents of about 10–25 kA produced plasmas with densities and temperatures of about 10^{16}–10^{17} cm^{-3} and 2–4 eV. The discharges lasted for about 120 μsec and were unpinched because of the very short diffusion time ($\tau \sim 2$ μsec) of the magnetic fields in the cool plasma (2 eV) produced by the arc.

Scattering measurements with long-wavelength lasers from dense low-temperature plasmas are generally very difficult to perform since whenever the input laser power is sufficient to produce a discernible scattering signal, it is also sufficiently intense to perturb the plasma by heating it. In this experiment, the problem of heating the plasma was overcome by the use of a heterodyne technique[10,11] which is capable of boosting the detected signal many orders of magnitude; as a result, it permits the use of a relatively low-power laser ($\sim$200 W) which does not perturb the plasma significantly.

A schematic of the heterodyne scattering configuration is shown in Fig. 2. First, a small fraction of

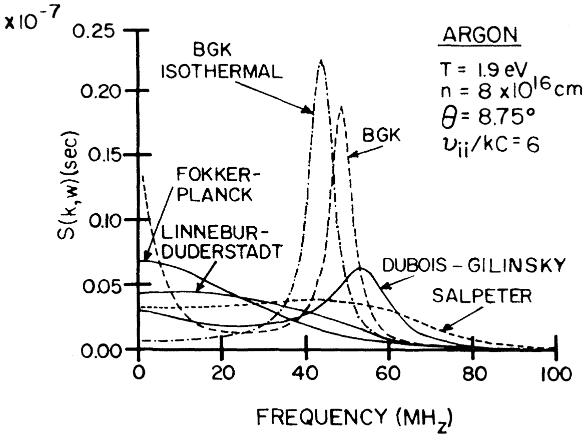

FIG. 1. Ion-acoustic spectra for a collisional argon plasma as calculated from the various collisional theories (Refs. 1–5) and compared to a collisionless calculation [Salpeter (Ref. 9)].

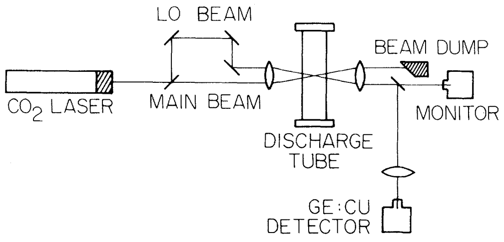

FIG. 2. Diagram of the optical system and scattering geometry.

the main laser beam is split off to form a local oscillator beam and, subsequently, the main and local oscillator beams are focused into the plasma with a 10-cm–focal-length lens. Any light that is scattered out of the main beam and into the solid angle subtended by the local oscillator beam is imaged onto a liquid-helium–cooled Ge:Cu detector. The nonlinear mixing of the scattered and local oscillator beams produces a detected photocurrent, which contains the plasma fluctuation spectra. These spectra are then extracted from the detector photocurrent with a tunable electronic filter ($\Delta F = 6$ MHz) which is scanned on a shot-to-shot basis.

Initial scattering measurements were made in argon plasmas ($n_e = 10^{17}$ cm^{-3}, $T_e = 1.95$ eV) for the two cases of $\vec{k}$ parallel and perpendicular to the discharge current. The observed spectra are displayed in Fig. 3 and show substantial peaking near the ion-acoustic frequency (50 MHz at 2 eV) which is indicative of collisional undamping of ion-acoustic waves that are otherwise heavily Landau damped. Each data point corresponds to a scattering signal averaged over fifty discharges of the arc and the error bars are derived from the standard deviations of the mean.

Even though the observed enhancement of the ion-acoustic resonance is indicative of collisional plasma behavior, there is a possibility that such enhancement could have been produced by collisionless mechanisms such as unequal electron and ion temperatures ($T_e > T_i$) which substantially reduce Landau damping of ion-acoustic waves driven by the discharge current. However, unequal electron and ion temperatures are unlikely because the collisional equilibration time between ions and electrons (70 nsec) is much shorter than the plasma lifetime (120 μsec) and because a temperature differential sufficient to produce the observed resonance amplitude would also shift the resonance position by a factor of 2,[12] which was not observed.

The effect of the discharge current was not expected to be very important because the electron drift velocity due to the current was only 20% of the ion-acoustic velocity. In fact, the 30% enhancement of the fluctuation spectrum parallel to the current agreed with the predictions of simple linear theory[13] which give the degree of enhancement as $C_s/(C_s - V_d)$. As a result, it can be concluded that the observed spectra with $\vec{k} \perp \vec{J}$ were due to thermal ion-acoustic fluctuations and that the observed enhancement was due to collisional effects.

A comparison of the theories displayed in Fig. 1 with the scattering results required that the data originate from thermal fluctuations. Final data were, therefore, taken with $\vec{k} \perp \vec{J}$. Specifically, scattering spectra from both helium (2.3 eV, 1×10^{17} cm^{-3}) and argon (1.95 eV, 1×10^{17} cm^{-3}) plasmas were each measured at scattering angles of 8.75° and 4.7°. These spectra are shown in Figs. 4

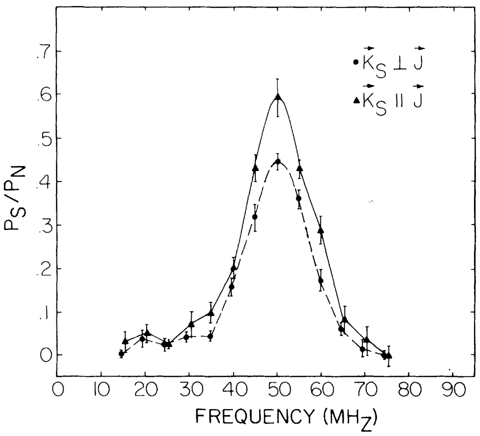

FIG. 3. Scattered ion-acoustic spectra for the two cases where $\vec{k} \parallel \vec{J}$ and $\vec{k} \perp \vec{J}$ which demonstrate the effect of the discharge current.

and 5 and, as expected, they show substantial enhancement and narrowing, with the peak amplitudes being about 10 times the predicted amplitudes of collisionless theory.

The theoretical curves presented alongside the data are due to the Bhatnagar-Gross-Krook (BGK) theory, which was the most successful in reproducing the data for the specific plasma temperatures and densities that were measured by independent diagnostics. No free parameters were used in the calculations other than a normalization of the calculated spectra to the peak amplitude of the data so as to allow for the uncertainty (factor of 2) in the absolute intensity calibration of the detection system. The BGK theory also predicts the enhancement of entropy fluctuations at zero frequency; however, this could not be verified in the present experiment because the finite pulse length of the laser imposed a lower limit on the detection frequency.

Even though the general shape and position of the ion-acoustic resonances is predicted fairly well by the BGK theory, there exists a discrepancy between the measured and predicted widths of the resonances. This difference, except for the 4.7° argon spectrum, cannot be accounted for by the finite resolution of the experiment ($\Delta F = 6$ MHz, $\Delta k/k = \pm 0.05$). The basis for this discrepancy probably lies in the fact that ion-electron collisions, in comparison to ion-ion or electron-electron collisions, have been assumed to be unimportant in the theoretical formalism. For plasma conditions encountered in this experiment, however, such an assumption is most likely invalid because the collisional equilibration time between electrons and ions [$\tau_{\mathrm{eq}}(\mathrm{He}) \approx 9$ nsec, $\tau_{\mathrm{eq}}(\mathrm{Ar}) \approx 70$ nsec] is comparable to the period of ion-acoustic oscillations. The main effect of collisional coupling between electrons and ions would be to increase the effective thermal conductivity of the ions and thus to increase the damping of the ion-acoustic waves, therefore, increasing the width of the observed resonances.

In conclusion, small-angle scattering measurements of thermal ion-acoustic fluctuations from highly collisional ($\nu_{ii}/kC_s \approx 5$–13) argon and heli-

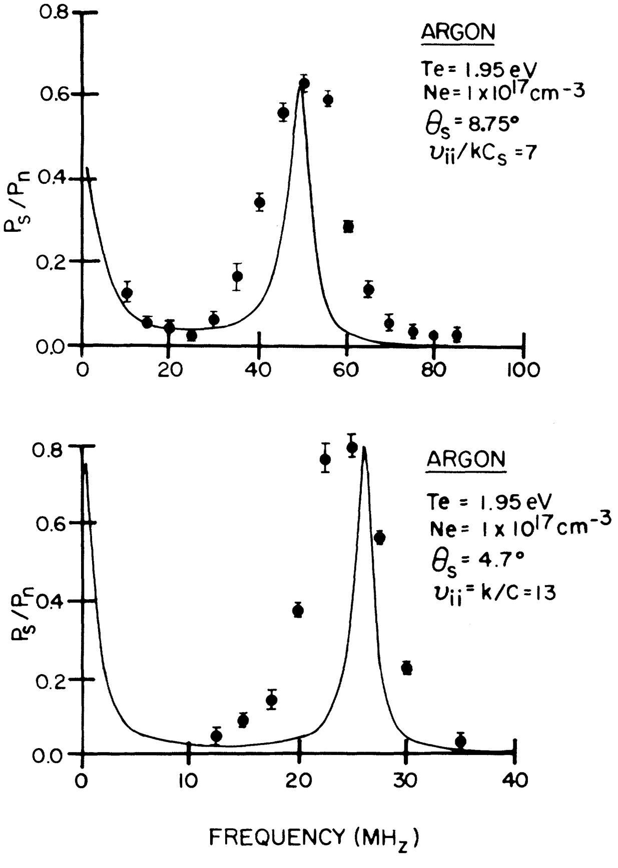

FIG. 4. Scattered light spectrum in argon for the 4.7° and 8.75° scattering angles. Calculated curve is due to the BGK theory (Refs. 1,5,12).

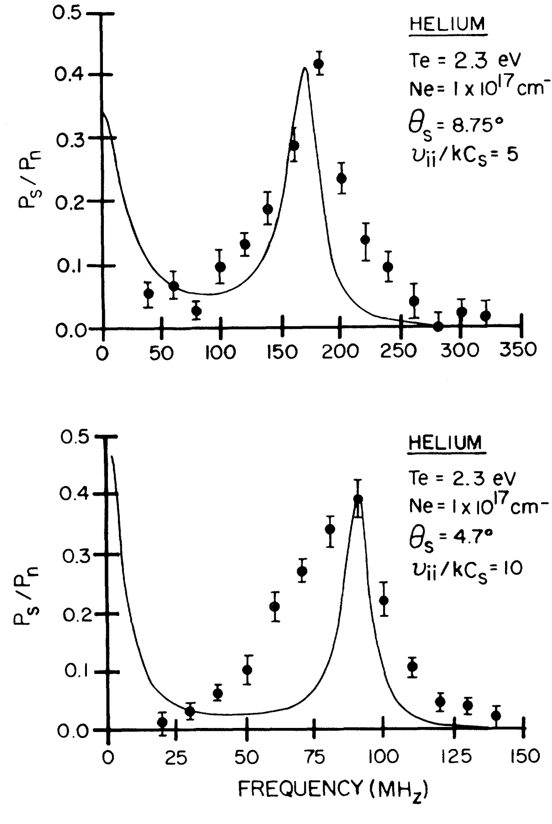

FIG. 5. Scattered light spectrum in helium for the 4.7° and 8.75° scattering angles. Theory curve is as in Fig. 4.

um plasmas have been obtained. These measurements show substantial enhancement of the ion-acoustic resonances due to collisional effects. A comparison to theoretical predictions calculated from independent measurements of temperature and density shows that the BGK theory is the most accurate in reproducing the data.

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[1] P. L. Bhatnagar, E. P. Gross, and M. Krook, Phys. Rev. **94**, 511 (1954).

[2] E. J. Linnebur and V. V. Duderstadt, Phys. Fluids **16**, 665 (1973).

[3] D. F. DuBois and V. Gilinsky, Phys. Rev. **133**, A1317 (1964).

[4] M. S. Grewal, Phys. Rev. **134**, A86 (1964).

[5] O. Theimer and M. M. Theimer, Nuovo Cimento Soc. Ital. Fis. B **65**, 207 (1981).

[6] E. Holzhauer, Phys. Lett. **62A**, 495 (1977).

[7] A. A. Offenberger and R. D. Kerr, Phys. Lett. **37A**, 435 (1971).

[8] J. H. Massig, Phys. Lett. **66A**, 207 (1978).

[9] E. E. Salpeter, Phys. Rev. **120**, 1528 (1960).

[10] R. E. Slusher and C. M. Surko, Phys. Fluids **23**, 472 (1980).

[11] E. Holzhauer and J. H. Massig, Plasma Phys. **20**, 867 (1978).

[12] A. N. Mostovych, "Laser Scattering Measurements of Thermal Fluctuations in Collisional Plasmas," Ph.D. thesis, University of Maryland, 1984 (unpublished).

[13] G. Bekefi, *Radiation Processes in Plasmas* (Wiley, New York, 1966).