Ion Acoustic Waves in Ultracold Neutral Plasmas

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We photoionize laser-cooled atoms with a laser beam possessing spatially periodic intensity modulations to create ultracold neutral plasmas with controlled density perturbations. Laser-induced fluorescence imaging reveals that the density perturbations oscillate in space and time, and the dispersion relation of the oscillations matches that of ion acoustic waves, which are long-wavelength, electrostatic, density waves.


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Collective wave phenomena are central to the transport and thermodynamic properties of plasmas, and the presence of a rich spectrum of collective modes is a distinctive feature that separates this state of matter from a simple collection of charged particles [1]. In ultracold neutral plasmas (UNPs) [2,3], which are orders of magnitude colder than any other neutral plasma and can be used to explore the physics of strongly coupled systems [4–6], little work has been done to study collective modes [7–10]. Here we employ a new technique for creating controlled density perturbations to excite ion acoustic waves (IAWs) in an UNP and measure their dispersion relation. This flexible technique for sculpting the density distribution will open new areas of plasma dynamics for experimental study, including the effects of strong coupling on dispersion relations [11–14] and nonlinear phenomena [3,10,15,16] in the ultracold regime.

UNPs are formed by photoionizing laser-cooled atoms near the ionization threshold. They stretch the boundaries of traditional neutral plasma physics and have extremely clean and controllable initial conditions that make them ideal for studying phenomena seen in more complex systems, such as plasma expansion and equilibration in high-energy-density laser-matter interactions [5] and quark-gluon plasmas [6]. UNPs have shown fascinating dynamics, such as kinetic energy oscillations that directly reflect the strong coupling of ions [5,17]. Strong coupling arises when particle interaction energies exceed the kinetic energy [4]. It is important in many fields of physics spanning classical to quantum behavior [5,6,18,19] and gives rise to phase transitions and the establishment of spatial correlations of particles [4]. These studies complement experiments probing strong coupling in dusty plasmas [18] and non-neutral plasmas of pure ions or electrons [19].

Previous experimental studies of collective modes in UNPs were limited to excitations of Langmuir (electron density) oscillations with radio frequency electric fields [7,8], which did not determine a dispersion relation and were relatively insensitive to dynamics of the strongly coupled ions. A high-frequency electron drift instability was observed in an UNP in the presence of crossed electric and magnetic fields [9]. Spherically symmetric ion density modulations were shown to excite IAWs in numerical simulations of UNPs [10]. Here we excite IAWs through direct imprinting of ion density modulations during plasma formation and image them in situ with time resolved laser-induced fluorescence [20].

Low-frequency electrostatic waves, which are longitudinal ion density oscillations, are one of the most fundamental waves in a plasma along with Langmuir oscillations [21]. A hydrodynamic plasma description, assuming slow enough ion motion for electrons to remain isothermal and an infinite homogeneous medium, predicts the dispersion relation for frequency $\omega$ and wave vector $k$

$$\left(\frac{\omega}{k}\right)^2 = \frac{k_B T_e/M}{1 + k^2 \lambda_D^2},$$

where $M$ is the ion mass, $T_e$ is electron temperature, and $\lambda_D = \sqrt{\epsilon_0 k_B T_e/n_e e^2}$ is the Debye screening length, for electron density $n_e$ and charge $e$. We have neglected an ion pressure term because the ion temperature satisfies $T_i \ll T_e$ in UNPs. In the long-wavelength limit, which is the focus of this study, this mode takes the form of an IAW with $\omega = k \sqrt{k_B T_e/M}$, in which ions provide the inertia and electrons provide the restoring pressure.

IAWs are highly Landau damped unless $T_i \ll T_e$ [1]; however, they have been studied in many types of high-temperature laboratory plasmas [15,16,22]. Closely related to this work, acoustic waves of highly charged dust particles in dusty plasmas have been studied experimentally [23,24] and theoretically [11–14] because of the possibility of observing the effects of strong coupling on the dispersion relation. Transverse shear dust waves have been observed [25,26], which are a clear signature of strong coupling, and phonon spectra have been seen in 2D crystals [27]. But to date effects of strong coupling on acoustic (longitudinal) waves in three dimensions have been masked by damping due to collisions with background neutral gas [11,13,28]. Beyond fundamental interest, IAWs are invoked to explain wave characteristics observed in Earth’s ionosphere [29] and transport in the solar wind, corona, and chromosphere [30].

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UNPs are created through photoionization of laser-cooled strontium atoms from a magneto-optical trap (MOT) [3]. The MOT operates on the $^{88}$Sr $^1S_0 - ^1P_1$ resonance at 461 nm [31], trapping $\sim 3 \times 10^8$ atoms at $\sim 10 \text{ mK}$ with a spherical Gaussian density distribution. Photoionization is a two-photon process: the first from a pulse amplified laser beam operating on the Sr trapping transition, and the second from a 10 ns Nd:YAG pumped dye laser tunable around 412 nm [3]. This process ionizes $\sim 50\%$ of the atoms, and the plasma inherits its density distribution from the neutral atoms. Effects of un-ionized atoms on the plasma are not observed because of the fast time scales of the experiment and small neutral-ion collision cross sections.

Resulting electron temperatures are determined by the excess energy of the ionizing photons above threshold, and are adjustable from 1–1000 K. Ion temperatures of approximately 1 K are set by disorder-induced heating [17,32,33] during the thermalization of the ions, and result in strongly coupled ions in the liquidlike regime [3,4]. Density distributions are spherical Gaussians, $n(r) = n_0 \exp(-r^2/2\sigma_0^2)$, with $n_0 \sim 10^{15}$ cm$^{-3}$ and $\sigma_0 \sim 1.5 \text{ mm}$, yielding average $\lambda_p$ from 3–30 $\mu\text{m}$. In our experiments, no magnetic field is applied.

IAWs were excited by passing the 412 nm ionizing beam, after its first pass through the plasma, through a periodic transmission mask and retroreflecting it back onto the plasma. This creates a $\sim 10\%$ plasma density modulation with wavelength set by the period ($\lambda_0$) of the mask [Fig. 1(a)]. The mask pattern is translated to align a density minimum to the center of the plasma. Small higher-harmonic IAWs, arising from the square-wave nature of the mask, were observed for longer period gratings, but no effect on the fundamental wave was detected.

For a diagnostic, ions are optically excited on the primary $\text{Sr}^+$ transition, $^2S_{1/2} - ^1P_{1/2}$, with a tunable, narrow band ($\sim 5 \text{ MHz}$) laser at $\lambda = 422$ nm, propagating approximately perpendicular to the ionizing laser [3,20]. The 422 nm beam is masked with a 1 mm slit so it only illuminates a central slice of the plasma, and resulting laser-induced fluorescence emitted close to perpendicular to the plane of the ionizing and 422 nm beams is imaged onto an intensified CCD camera with a resolution of 13 $\mu\text{m}$.

Data from $\sim 50$ repetitions of the experiment are summed to form a single image, $F(x, y, \nu)$, that has a frequency ($\nu$) dependence reflecting the natural linewidth and Doppler broadening of the transition [3,20]. Forty images are recorded at evenly spaced frequencies for the 422 nm laser spanning the full spectral width of the signal. These are summed to obtain a signal proportional to the density of the plasma in the illuminated plane ($z = 0$),

$$\sum_{\nu} F(x, y, \nu) \approx n_i(x, y, z = 0). \quad (2)$$

Density averaging along the imaging axis ($z$) is small because fluorescence is only excited in a sheet of plasma.
sion is self-similar and the characteristic plasma size changes according to [3]

\[ \sigma(t) = \sigma_0 \left(1 + \frac{t^2}{\tau_{\text{exp}}^2}\right)^{1/2}, \quad (3) \]

where \( \tau_{\text{exp}} = \sqrt{M \sigma_0^2 / k_B T_e(0)} \) is the characteristic plasma expansion time, which ranges from 10–30 \( \mu \)s in this study. Associated with expansion is an adiabatic cooling of electrons according to \( T_e(t) = T_e(0) / (1 + t^2 / \tau_{\text{exp}}^2) \), which shows that expansion is driven by a transfer of electron thermal energy to the kinetic energy of ion expansion. In direct measurements of plasma size and spectral measurement of ion expansion velocity [20], we saw no deviation in expansion time, which ranges from \( 1 \times 10^5 \), to \( 70 \) K. Initial amplitude \( A_0 \), frequency \( \omega_0 \), and damping rate \( \Gamma \) are allowed to vary in the fits, which match the data very well (Fig. 3). Decreasing frequency with time was observed in simulations of spherical IAWs [10].

For a range of initial electron temperatures and mask periods, we extract \( \omega_0 \) and \( k_0 \) and calculate the dispersion of the excitations, as shown in Fig. 4. The excellent agreement with theory, Eq. (1), confirms that these excitations are IAWs. The planar standing-wave model captures the dominant behavior of the wave, and to a high accuracy there is no deviation from the standard dispersion relation in spite of the plasma’s finite size, expansion, and inhomogeneity density.

Following on this initial study of ion density excitations in an UNP, there are many topics to explore. The observed...
waves show damping times on the order a few oscillation periods, which is faster than predicted for Landau damping [1]. The nature of the boundary conditions and effects of density inhomogeneity and plasma expansion on IAWs should be explored, and may be important for understanding damping. The mask period is currently limited by diffraction effects, but this can be overcome by modifying the optical configuration. For mask periods approximately 5 times smaller, we can probe beyond the acoustic region of the dispersion relation. In this regime, the effects of strong coupling on dispersion are also predicted to be important, and there are many theoretical predictions that have not been tested [11–14]. Furthermore, obtaining higher spatial frequency will allow the possibility of studying waves in smaller regions of the plasma with constant density and $\lambda_D$, making it easier to compare experiments and theoretical predictions. In addition, the wave can be studied in velocity space with resolved fluorescence spectroscopy [20], and different initial density distributions can be designed to investigate solitons [15], instabilities [16], asymmetric excitations, and shock waves [3,10].

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Note added in proof.—IAWs have been studied in the presence of a 1D density gradient [34], and a theoretical treatment of IAWs in UNPs was recently published [35].


