Observation of Stimulated Electron-Acoustic-Wave Scattering

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(Received 26 April 2001; published 24 September 2001)

A diffraction-limited laser interacts with a plasma whose conditions are uniform on the scale of the focused laser spot. Two distinct, narrow waves are observed in the backscattered spectrum with phase velocities of $v_\phi/v_e = 1.4 \pm 0.08$ and 4.2 ± 0.1, where v_e is the electron thermal speed. The high-velocity wave is ordinary stimulated Raman scattering (SRS) from a Langmuir wave. The low-velocity wave corresponds to stimulated scattering from an electron-acoustic wave (SEAS), and implies strong electron trapping. Previous SRS data from low-density plasmas are reinterpreted in terms of SEAS.

DOI: 10.1103/PhysRevLett.87.155001 PACS numbers: 52.35.Fp, 52.35.Mw, 52.35.Sb, 52.38.–r

The nonlinear evolution of electrostatic waves in plasmas is an important topic in plasma physics. In laser plasma research, intense lasers can couple to weakly damped electrostatic waves in the plasma and produce scattered light waves from these modes. Two plasma modes that have been studied extensively in unmagnetized plasmas are the electron plasma wave (EPW) [1], and the ion acoustic wave (IAW) [2]. Both of these modes are weakly damped for a broad range of laser plasma conditions. Coupling of the intense laser field to these modes can result in significant loss of laser energy via stimulated Raman scattering (SRS) and stimulated Brillouin scattering [3].

Early authors [2,4,5], examining the linearized Vlasov electrostatic dispersion relation (which ignores particle-trapping effects), also noted solutions which they termed electron-acoustic waves (EAW). Their dispersion relation in the long wavelength limit is $\omega \approx 3.6kv_e$, where (ω, k) are the electrostatic wave frequency and wave number, $v_e = \sqrt{T_e/m_e}$ is the electron thermal velocity, and the constant 3.6 is obtained by finding the least damped root for this linear mode [2,5]. These intermediate phase velocity modes ($v_\phi = \omega/k$) were obtained in addition to the weakly damped slow phase velocity IAW ($v_\phi/v_e \ll 1$), and the high phase velocity EPW ($v_\phi/v_e \gg 1$). The EAW solutions were discounted by those authors due to their huge linear damping with Maxwellian distributions, $-\mathrm{Im}(\omega)/\mathrm{Re}(\omega) \geq 1$ [2,5]. However, other studies of nonlinear Vlasov-Maxwell (VM) systems [6–8] found that electrons trapped in the wave electrostatic potential can result in undamped solutions, so-called BGK modes [6], allowing the EAW to exist. The nonlinear dispersion, however, produces a lower phase velocity EAW ($\omega \approx 1.31kv_e$) [7,8] compared to the least-damped linear EAW solution ($\omega \approx 3.6kv_e$).

In this Letter, we report the observation of stimulated scattering from an electrostatic wave whose phase velocity is between an EPW and an IAW. The experiments are performed using a laser plasma in the single hot spot (SHS) configuration [9,10], where the plasma conditions are initially uniform on the scale of the laser focal spot. The backscattered spectrum is measured and found to contain two narrow modes with phase velocities of $v_\phi/v_e = 1.4$ and 4.2, and wave numbers $k\lambda_D = 0.29$ and 0.27, respectively, where $\lambda_D = v_e/\omega_p$ is the electron Debye length, and ω_p is the electron plasma frequency. The high v_ϕ/v_e wave is due to SRS from an EPW. The low v_ϕ/v_e wave is due to stimulated electron-acoustic-wave scattering (SEAS), and its phase velocity is consistent with the acoustic branch of a small amplitude BGK mode. Previous data from inhomogeneous laser plasma experiments, which were formerly viewed as SRS from unrealistically low plasma density, are reinterpreted in terms of SEAS. The nonlinear dispersion relation suggests an ultimate limit to the accessibility of such scatter to electrostatic waves with $k\lambda_D < 0.53$.

The experiments were performed using the Trident laser facility [11], and the experimental configuration is described elsewhere [9,10]. A nearly diffraction-limited (single hot spot) laser is focused into and interacts with a fully ionized, preformed C_8H_8 plasma with electron temperature $T_e = 350 \pm 50$ eV, electron density $n_e = (1.2 \pm 0.1) \times 10^{20}$ cm^{-3}, and transverse flow Mach number $M = 2.5 \pm 0.3$. The plasma conditions for this experiment were measured using collective Thomson scattering [9], interferometry [12], and inferred from the SRS spectra (with a small correction using the measured T_e). The 527-nm SHS laser is focused using a $f/4.5$ lens to a spot diameter of $f\lambda_0 = 2.5 \pm 0.15$ μm, and the focal depth is approximately $7f^2\lambda_0 \approx 75$ μm [9,10]. The SHS laser pulse is 200 ± 10 ps Gaussian, and a peak vacuum intensity of 1.6×10^{16} W/cm^2 is obtained at best focus for a nominal energy of 500 mJ. The measured plasma density scale lengths transverse and parallel to the SHS focus are ~200 and ~1000 μm, respectively, such that the plasma initial conditions are homogeneous on the scale of the focal spot volume.

The time-resolved spectra and energy of backscattered light are measured within the focusing lens using streaked

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spectroscopy and an absolutely calibrated photodiode. Because of the limited dynamic range of the spectrometer, the SRS and SEAS spectra are measured on separate experiments with nearly identical laser and plasma conditions. The temporal and spectral resolution are ~30 ps and 1.8 nm for the SRS spectra, and ~100 ps and 0.25 nm for the SEAS spectra. Figure 1 shows a composite time-integrated backscattered spectrum from two separate experiments at an intensity of $\sim 10^{16}$ W/cm^2. The spectrum shows a bright narrow peak at 654 nm (spectral width ~7 nm) corresponding to ordinary SRS scattering from an EPW with $k\lambda_D \approx 0.27$ inferred from the plasma conditions and wave matching conditions. The SRS reflected energy was ~0.06 of the incident laser energy. A spectrum in the range from 540–600 nm was recorded on a separate experiment with identical laser and plasma conditions. A narrow peak, which we refer to as the SEAS mode, was observed at 566.5 nm (spectral width ~5 nm) whose amplitude is ~3000× lower than the SRS peak. The energy in the SEAS mode was at most 2.0×10^{-5} of the laser energy. The SEAS and the SRS modes coexist in time, and their time histories roughly follow the laser pulse shape.

The intensity of the SHS laser was varied between $(0.3–1.6) \times 10^{16}$ W/cm^2. The SEAS reflectivity varied from $\leq 10^{-8}$ up to 2.0×10^{-5} over this range of intensity. At an intensity of $\sim 3 \times 10^{15}$ W/cm^2, the SEAS mode dropped below the detection threshold ($\leq 10^{-8}$), although SRS was still observed at the 0.005 level. The SRS reflectivity varied between 0.005–0.07 over this range. The SEAS mode central wavelength and width remained constant over this range of intensities. At an intensity of 1.6×10^{16} W/cm^2, the SEAS mode broadened out to shorter wavelengths (~557–568 nm), but the main spectral feature centered at 566.5 ± 2.5 nm was still dominant in the SEAS spectrum. The EPW due to SRS was

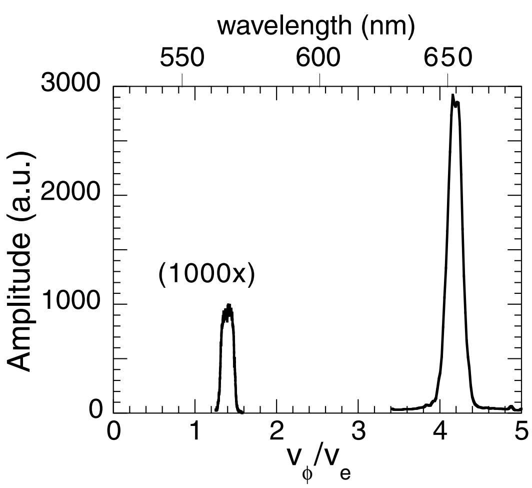

FIG. 1. Plot of SEAS and SRS backscatter spectrum versus electrostatic wave v_ϕ/v_e for the single hot spot experiment. SEAS mode is shown 1000× larger. Upper axis corresponds to the scattered light wavelength.

monitored by collective Thomson scattering for this experiment, and showed broadening toward shorter wavelengths, likely due to thermal self-focusing at this high intensity [10].

The ratio of the phase velocity to electron thermal velocity (v_ϕ/v_e) is easily and accurately computed for the electrostatic waves from the plasma conditions, the wave matching conditions, and the electromagnetic wave dispersion. The uncertainty for v_ϕ/v_e is ~7%, mostly attributed to the uncertainty in v_e. The spectrum in Fig. 1 is also plotted versus v_ϕ/v_e (bottom axis), and shows v_ϕ/v_e of 1.4 ± 0.08 (EAW) and 4.2 ± 0.1 (EPW) for the two waves.

The scattering from the low v_ϕ/v_e wave cannot be explained by SRS from a lower density EPW for the following reasons. First, one would expect $k\lambda_D \approx 3$ and $n_e \approx 4 \times 10^{18}$ cm^{-3} from the linear kinetic dispersion relation if this were an EPW with $v_\phi/v_e = 1.4$. The linear damping would be $-\mathrm{Im}(\omega/\omega_p) \approx 5$, and one could not get appreciable growth over the 1000 μm plasma length, not to mention over the 75 μm focal depth. Also, a wave with this v_ϕ/v_e would be in the nonresonant stimulated Compton scattering regime [13] and would produce a broad spectrum rather than the observed narrow spectrum. Previous laser plasma experiments have reported similar low phase velocity waves using collective Thomson scattering [14,15]. The discrete waves observed in those experiments were also between the IAW and EPW resonances, and were either too high or too low of a velocity to be physically explained as an IAW or EPW. However, the authors offered no quantitative explanation for the presence of such waves, which we present later in this paper.

Weakly damped EAW solutions, with frequencies between the ordinary IAW and EPW resonances, have been previously studied using the linearized Vlasov dispersion for two component (bi-Maxwellian) electron velocity distributions [16,17]. For our experiment, any such distribution function would have to yield weakly damped solutions simultaneously for both the EAW and the EPW at the observed phase velocities, i.e., $v_\phi/v_e \approx 1.4, 4.2$. We find no way to satisfy these constraints with such a distribution function. Further comparison with linear theory using other pathological distribution functions is unwarranted. Next, we present an explanation based on nonlinear traveling wave solutions to the VM system of equations that quantitatively predicts the phase velocities of both the EAW and the EPW resonances in the present experiment and those in Ref. [15], and explains the weak damping of these modes.

Nonlinear one-dimensional solutions of the VM equations have been studied by many authors [6–8] who found that strong trapping effects occur for even “small amplitude” electrostatic waves, resulting in undamped traveling waves (BGK modes). For the case of immobile ions, it was found that two undamped branches exist, the high-frequency branch corresponding to ω/ω_p and v_ϕ/v_e obtained for an EPW from ordinary linear theory, and the low-frequency branch corresponding to EAW, with $v_\phi/v_e \approx 1.31$ as $k \to 0$. Extensive studies of the low-frequency branch for both solitary and periodic traveling waves are reported in several papers by Schamel, who finds $v_\phi/v_e \approx 1.31\ (1 + k^2\lambda_D{}^2)$ in the small amplitude, small $k\lambda_D$ limit [7].

More recently, Rose and Russell studied nonlinear traveling wave solutions to the VM system including a dissipation term $\nu \approx v_e/f\lambda_0$ to account for the loss of trapped electrons out of the narrow dimension of a laser hot spot [18]. The inclusion of this small amount of dissipation in the VM system results in weakly damped modes rather than the undamped modes obtained in Refs. [7,8]. A nonlinear dielectric function, similar to that considered in Cohen *et al.* for ion waves [19], was obtained which agreed with VM simulations using a prescribed external potential. Figure 2a shows a plot of the nonlinear dielectric function $1/|\varepsilon|$ versus v_ϕ/v_e for our plasma conditions, and an electrostatic potential $e\Phi/T_e = 0.008$. Also shown is a plot of $1/|\varepsilon|$ from linear theory. The nonlinear theory predicts two weakly damped resonances at $v_\phi/v_e = 1.45$ and 4.19, and predicts the EAW resonance to exist over a reasonable range of dissipation ($\nu/\omega_p < 0.01$), and is plotted here for $\nu/\omega_p = 0.002$. Some amount of dissipation, while perhaps not quantitative, is in qualitative agreement with the observations since the EAW mode is much weaker than the EPW mode. It is also worth noting that solving for $\mathrm{Re}(\varepsilon) = 0$, for real v_ϕ and using ε from linear theory, one does obtain roots at $v_\phi/v_e = 1.41$ and 4.16, although the lower root is heavily damped, $\mathrm{Im}(\varepsilon) \gg 1$ [4,7].

The nonlinear dispersion relation depends not only on (ω, k), but also on the dissipation rate ν, and the wave electrostatic potential, $e\Phi/T_e$. Figure 2b shows a plot of (ω, k) from the nonlinear dispersion relation for a range of wave amplitudes. The dispersion relation for $e\Phi/T_e = 0$ is identical to that shown in Fig. 4 of Ref. [8(b)]. While this model is not complete, it offers a quantitative explanation for v_ϕ/v_e of the observed waves, and a qualitative explanation for their amplitudes. The EAW does not exist as a bona fide mode unless trapping is important, and understanding the initialization of this process requires further theoretical work. Details regarding the VM solutions including dissipation and the resulting nonlinear dispersion relation will be published elsewhere [18].

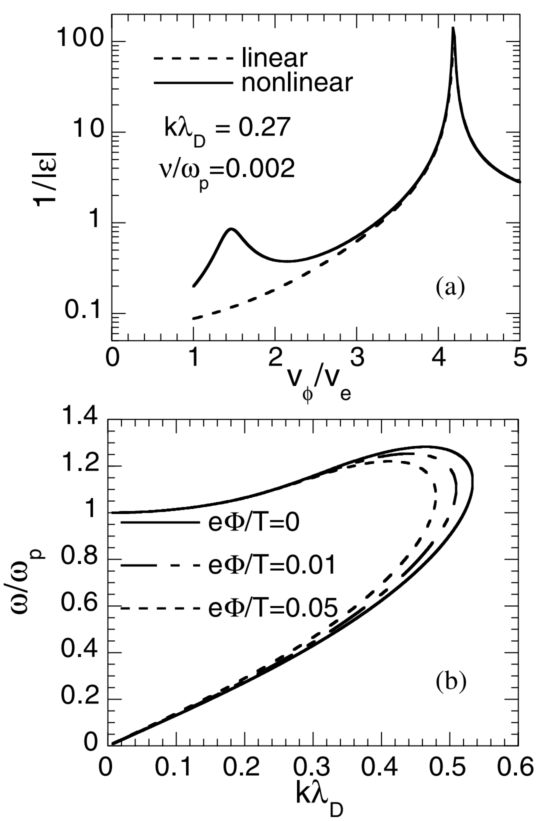

FIG. 2. (a) Plot of the nonlinear dielectric function, $1/|\varepsilon|$, versus v_ϕ/v_e showing the EAW and EPW resonance (solid line), and the linear dielectric function, which shows only the EPW resonance (dashed line); (b) nonlinear dispersion relation (ω, k) for various electrostatic potentials $e\Phi/T_e$. The upper branch is EPW; the lower branch is EAW.

Given the resonance cutoff for $k\lambda_D > 0.53$ predicted by the nonlinear dispersion relation [8,18], it is worthwhile to reexamine backscattered spectra from inhomogeneous plasmas. An experiment was performed using a random-phase-plate (RPP) smoothed interaction laser in similar plasma conditions as for the single hot spot experiment. The RPP focal spot size was $\sim$200 μm, the focal depth was $\sim$1000 μm, and the average laser intensity was $\sim 10^{15}$ W/cm^2, such that the high intensity laser interacted with a range of densities. The measured backscattered spectrum was continuous and covered the range between $v_\phi/v_e \approx 1$–4, rather than the two discrete waves observed in the SHS experiment. A significant fraction of scattered energy was observed for $v_\phi/v_e \approx 1$–2.

Other experiments have observed similar broadband backscattered spectra. Figure 3 shows the backscattered spectrum obtained from a previously published experiment using a RPP-smoothed 527-nm laser in an exploding foil plasma (see Fig. 1c of Ref. [20]), plotted versus both v_ϕ/v_e ($T_e = 2$ keV) and the scattered light wavelength. A significant fraction of the scattered energy is also observed from electrostatic waves with $v_\phi/v_e \approx 1$–2. Because of the huge damping predicted by linear theory and the inadequate system lengths, no satisfactory explanation can be proposed for significant scatter from these low v_ϕ/v_e waves based solely on SRS or SCS [20]. Rather, using the nonlinear dispersion relation resulting from trapping, a merger of the SEAS and SRS spectra seems to be a more likely explanation, since it predicts both the weak damping at low v_ϕ/v_e inferred from the experiment, and the range of v_ϕ/v_e measured.

The nonlinear dispersion relation also predicts the wavelengths for the two discrete EPW and EAW observed by Thomson scattering in Fig. 8 of Cobble *et al.* [15]. Using the nonlinear disperson relation and the plasma conditions

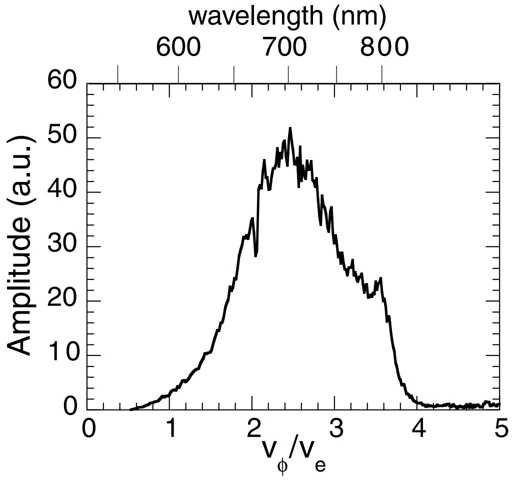

FIG. 3. Plot of backscatter spectrum versus electrostatic wave v_ϕ/v_e from the inhomogeneous plasma in Ref. [20]. Upper axis corresponds to the scattered light wavelength.

of that experiment, the Thomson scattered spectra would have peaks at ~415 nm, corresponding to the EPW from SRS, and at ~367 nm corresponding to the EAW from SEAS. This fits their results well, where the observed Thomson scattering from the low v_ϕ/v_e mode is centered at ~362 nm. The observations by Labaune *et al.* [14] show Thomson scattering spectra integrated over wave numbers between $k = 0.1\text{--}3.8k_0$ ($k_0 = 2\pi/1.05\ \mu$m in Ref. [14]). While not as quantitative as our comparison with Ref. [15] due to the broad range of wave numbers probed, the nonlinear dispersion would predict the EAW frequencies observed in Ref. [14] to fall within this range of k space. We speculate that the relative amplitude of SEAS to SRS is larger for any given hot spot in the RPP case (in contrast to the single hot spot case) due to a flattened "background" distribution function at the EAW phase velocity from neighboring hot spots which also support SEAS. Therefore, one might expect more SEAS for the RPP case. Other effects, such as SRS saturation, may also be important.

One final note regarding predictions of the nonlinear dispersion relation is the implications of the resonance cutoff for electrostatic waves with $k\lambda_D > 0.53$. The present design for ignition targets on the National Ignition Facility has $T_e = 5$ keV and $n_e \sim 10^{21}$ cm^{-3} so that $k\lambda_D \approx 0.4$ for SRS [21]. This is a concern since high SRS reflectivity has been observed for $k\lambda_D \approx 0.3\text{--}0.45$ in large plasmas [22]. The nonlinear dispersion relation would predict that SRS and SEAS are inaccessible for $T_e = 5$ keV and $n_e \leq 7 \times 10^{20}$ cm^{-3}, and these conditions might provide a new design point for ignition targets in the event of large, uncontrollable backscattering.

In summary, we have observed stimulated scattering from an EAW and an EPW. A nonlinear dispersion relation, which includes trapping effects, predicts the phase velocities and the weak damping for these waves. The linear dispersion relation, which ignores trapping, cannot match the observations assuming physical electron distributions. Previous laser-plasma experiments are reinterpreted using the nonlinear dispersion relation, and a clearer understanding for the existence of scattering from weakly damped, low v_ϕ/v_e electrostatic waves is provided.

The authors gratefully acknowledge useful discussions with S. H. Batha, A. Bers, J. J. Dorning, S. P. Gary, T. J. Murphy, and H. Schamel. We also acknowledge technical support from the Trident operations staff and the Target Assembly staff. This work was performed under the auspices of the U.S. Department of Energy by LANL under Contract No. W-7405-ENG-36.

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