case with $\Delta\omega$ being replaced by the average mismatch due to density inhomogeneity. Clearly, if l is the characteristic wavelength of the unstable waves, then $\langle\Delta\omega\rangle$ should be approximately given by $(\lambda_D/l)^2\omega_p$. However, from hindsight we see that l is nothing but the typical Airy scale length $(L/k_D^2)^{1/3}$. This together with the generalized marginal stability condition immediately gives $V_0/c \simeq (k_\perp L)^{-1}$, provided that $k_\perp l \ll 1$. The last condition is the same as $k^2 \gg 1$ which we used in deriving Eq. (12). The above simple argument seems to be sufficiently general for various temporal instabilities in an inhomogeneous plasma and should deserve further investigations.

The electrostatic $2\omega_{pe}$ instability clearly would appear to be an important nonlinear absorption mechanism for plasma heating both in controlled thermonuclear reactions and in laser-pellet experiments because of its low threshold and large growth rate. It is especially attractive in the sense that the unstable products will eventually be locally absorbed by the plasma near the cutoff because of strong Landau damping in the underdense region.

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Turbulence Spectrum Observed in a Collision-Free θ-Pinch Plasma by CO_2 Laser Scattering

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Turbulence generated by a rapidly imploding current sheath in a high-voltage θ pinch has been investigated by CO_2 laser scattering and by emission spectroscopy of forbidden-line satellites in helium. Waves indicative of a saturated ion-sound instability are seen in the current sheath. In a region well behind the sheath, waves are seen with wave numbers near k_D. These waves may be the result of mode coupling from short-wave-number turbulence generated earlier by the passage of the current sheath.

Plasma-heating turbulence has been seen in several laboratory experiments featuring the application of rapidly rising current pulses to low-density ($n_e = 10^{13}$ cm^{-3}) plasmas.[1] Plasma heating results from instabilities of the current stream which transfer energy to plasma waves followed by decay via mode coupling and damping into thermal energy. Several instabilities have been proposed as mechanisms by which heating may occur.[2-5] We report here the use of scattering of CO_2 laser radiation (10.6 μm) from a low-β [$\beta \equiv nkT(B^2/8\pi)^{-1}$] turbulent θ-pinch plasma to measure the spectra of density fluctuations. The scattering is supplemented by measurements of the magnitude of the electric field fluctuations by helium satellite spectroscopy. These observations provide a direct way to study the properties of the instabilities.

The experiments were done in the Maryland fast θ pinch which has been described elsewhere.[6] Conditions just prior to the heating pulse are $n_e = 1.6\times10^{13}$ cm^{-3}, $T_e = 0.5$ eV, and $B_0 \doteq 175$ G. The magnetic field which excites the instabilities reaches 1500 G in 280 nsec, and may be either parallel or antiparallel to the bias field B_0. Measurements were attempted in hydrogen, deuterium, helium, and argon plasmas using both parallel and antiparallel configurations. The largest and most consistent scattered signals were seen in the parallel-bias helium case on which we report here.

The Debye wave number $k_D = (4\pi n_e e^2/kT_e)^{1/2}$ is determined at one radius ($r = 13$ cm) by measuring the electron temperature and density by Thomson scattering of ruby laser light. Because of a very high level of plasma radiation, the scattered light was collected at an angle of 20° to the incident beam direction by a lens immersed in the

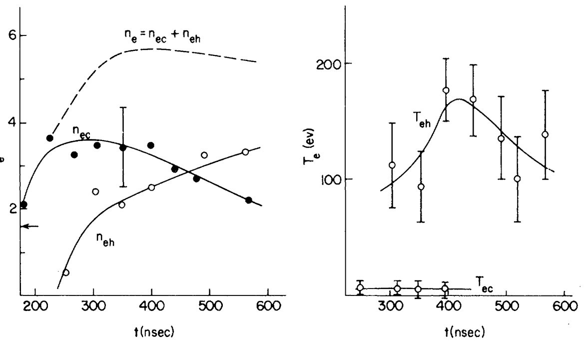

FIG. 1. Time history at $r=13$ cm of the electron density n_e and temperature T_e in the parallel-bias helium plasma. The subscripts c and h refer to cold and hot components of the distribution.

plasma. This increased the intensity of the scattered light by narrowing its spectrum. Results are shown in Fig. 1. The electron distribution function consists of two distinct components designated as "hot" and "cold." The hot component appears during the passage of the current sheath, the temperature reaching a maximum of about 160 eV near the end of the pulse. The cold group, whose temperature remains about 10 eV, shows an initial density increase by a factor of 2. After 250 nsec the density of the hot component rises steadily while the total density remains nearly constant.

The increase in density which has been observed is probably due to ionization of neutral gas by high-temperature electrons. This interpretation is supported by computer studies of ion orbits in the observed magnetic field, which show that little compression is to be expected at $r=13$ cm. Estimates of ionization rates also support this conclusion.[7]

Small-angle scattering at the CO_2 laser wavelength makes it possible to evaluate the spectrum of density fluctuations $\langle n_e^2(\vec{k})\rangle^{1/2}$ for the regime $|\vec{k}| \lesssim k_D$. The scattering geometry defines $\vec{k}=\vec{k}_0=\vec{k}_s-\vec{k}_i$, where $\vec{k}_i$ and $\vec{k}_s$ are the incident and scattered wave vector, respectively. The magnitude of $\vec{k}_0$ is related to the scattering angle through $k_0=2k_i\sin(\theta_s/2)$; θ_s is the scattering angle, and $k_0<k_D$ requires $\theta_s \lesssim 6°$ for our plasma conditions. Both the wave-number spectrum and the angular distribution of density fluctuations may be obtained by making changes in either the scattering angle or the direction of $\vec{k}_0$ with respect to the direction of the electron drift. The laser power available to us (~0.5MW) and detector (Ge:Hg photoconductor) sensitivity limit our observations to density fluctuations which enhance the total cross section by a factor of 100 or more above thermal levels, and avoidance of stray light from the incident beam requires θ_s to be greater than 2.5°. Other mechanical constraints limit the direction of $\vec{k}_0$ to be within a few degrees of the plane perpendicular to $\vec{B}_0$.

Observations of scattering at 10.6 μm are made with the scattering volume at $r=9$ and 13 cm. Two classes of scattered light signaling turbulence at k_0 are seen. The first is a narrow ($\lesssim 30$ nsec) pulse coincident with the current stream, isotropic in the r-θ plane, and seen only at $r=9$ cm. The second is a broad (~200 nsec) feature appearing well after the passage of the current stream. This feature is strongly peaked in amplitude along the direction of current flow and is seen at both radii.

The first pulse is observed with $k_0 \simeq 430$ cm^{-1} ($\theta_s=4°$) and $\vec{k}_0$ in the r-θ plane. Scattered signals are seen with $\vec{k}_0$ parallel, perpendicular, and antiparallel to the electron drift velocity v_d (θ direction) on successive machine pulses. For these directions, no consistent variations are observed in the shape, timing, or intensity of the scattered signals. The enhancement (P_k/P_t) is about 10^4. That is, we observe 10^4 times the scattered power which would be expected from a quiescent plasma with the same density. A coarse spectral analysis of this feature shows that the frequencies of the waves responsible for the enhancement are below $0.6\omega_{pe}$.

The second pulse appears well behind the current sheath at both 9 and 13 cm and the enhancement at both radii is about the same at $\theta_s=4°$ as that of the narrow pulse. The angular spectrum for this feature at $r=13$ cm is shown in Figs. 2(a) and 2(b). In 2(a) the enhancement factor P_k/P_t is shown as a function of φ_k, the angle of $\vec{k}_0$ away from the r-θ plane. The fluctuations fall off rapidly with a width of about 3° for $\theta_s=4°$. In the r-θ plane the spectrum is broader. Figure 2(b) shows the change with angle θ_k between $\vec{k}_0$ and $\vec{v}_d$ for $\theta_s=4°$. In 2(c) the wave-number spectrum is shown. In this case $\vec{k}_0$ remains parallel to $\vec{v}_d$ while the scattering angle ($\propto k_0$) is changed. We know that $k_D \simeq 1000$ cm^{-1} at this time.

Scattering in higher-density shocks have been reported previously by Daughney, Holmes, and Paul[8] and most recently by Kornherr *et al.*,[9] who have also tentatively identified scattering in the piston. In the case on which we report, no shock-piston separation is observed and no magnetic structure is seen during our second scattered feature.

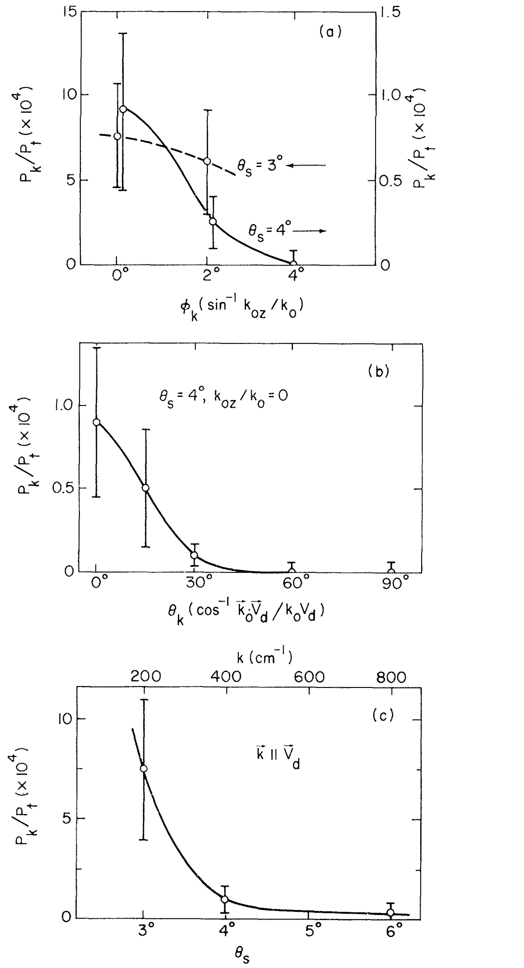

FIG. 2. Angular dependence of the scattering cross section relative to the thermal level for CO_2 scattering at $t = 600$ nsec and $r = 13$ cm. P_k/P_t is the ratio of the observed scattered power to the scattered power expected from a thermal plasma. (a) The angle φ_k is the angle of $\vec{k}_0$ out of the r-θ plane. The angular dependence is shown for two different scattering angles $\theta_s = 3°$ and $4°$. (b) The angular dependence of scattering measured from the current-stream direction $(\vec{v}_d)$ in the r-θ plane. (c) The scattering dependence on $|\vec{k}_0|$, keeping $\vec{k}_0$ parallel to $\vec{v}_d$.

We cannot explain the observed signals by effects other than scattering from plasma turbulence. A calculation shows that the radial density gradients are not large enough to refract a part of the main beam into the collection optics. Furthermore, we observe that the scattering is always much smaller in the antiparallel-bias helium case where the measured density gradients are larger.

Further evidence on the evolution of instabilities is provided by observation of forbidden line satellites near the allowed helium line He I 4922 Å.[10] The satellite intensity gives a measurement of the integrated electric field fluctuations, $\int \langle E^2(\vec{k})\rangle^{1/2} d^3k$. The intensity of the wave fields is observed for $6 \leq r \leq 12$ cm. The field fluctuations rise with the arrival of the current stream in the view of the dectector, reaching a broad maximum of 6 kV/cm and persisting until $t = 500$–600 nsec.

We consider now the scattered feature which appears in the early part of the current sheath at 9 cm. In this region Joule heating, and/or the beam cyclotron instability, can raise the electron temperature to 10 eV in about 10 nsec, setting up the conditions $(T_e > T_i)$ for ion wave growth.[11] Conditions for the Buneman electron-ion instability are met only briefly in the current sheet.[12] Ion sound is unstable so long as the electron drift speed remains larger than $c_s = (kT_e/m_i)^{1/2}$ which is just over 100 nsec in this case. The sudden termination of the scattered signal after 30 nsec must be due to a shift of the instability spectrum in k space caused by a decrease in k_D. Satellite observations show no change in the integrated fluctuating fields during this time. As soon as the condition $k_D < k_0$ is met, waves are strongly damped at the observed wave number k_0 and the scattered signal goes down. We can infer a lower limit on T_e at $r = 9$ cm from $k_D < k_0$ and from measurements of the initial radial density profile by Langmuir probes. The initial density is 2.5 times higher at $r = 9$ cm than at $r = 13$ cm; using this multiplication factor we estimate that the electron temperature must rise above 800 eV to cut off waves at k_0. The observed isotropy in the r-θ plane suggests a saturated ion-sound instability since this is unstable over a broad angular range and the wave numbers correspond roughly to those observed.

The second scattered feature appears well after the current sheath has passed over the scattering volume and at a time when radial-magnetic-field profiles show negligible gradients. Nevertheless, the scattering shows a distinct preference for the direction of $\vec{v}_d$. This fact coupled with the observation of this feature at both positions—with and without scattering in front—indicates to us that the two features are not related. We suggest that this feature may be the result of turbulence generated earlier by the current stream at short wave numbers which has diffused by mode coupling to the observed wave number. Memory of the source of the instability v_d has been preserved through the conservation relation $\vec{k}_0 = \vec{k} + \vec{k}'$, where $\vec{k}$ or $\vec{k}'$ refer to the originally unstable modes. Two instabilities for which the instability criteria are met in the current sheath have angular dependences similar to those observed. They are the electron-cyclotron drift instability[4] and the lower-hybrid drift[2] instability.

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Propagation of Fourth Sound in Superfluid ^{3}He†

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Pressure waves propagate through a superleak in both ^{3}He-A and ^{3}He-B, showing that both are superfluids below T_c. Superfluid relative density is obtained from velocity measurements over a wide pressure range above and below the polycritical point.

We have shown using both transient and resonance methods that pressure waves propagate through a superleak in both ^{3}He-A and ^{3}He-B over a wide range of static pressure.[1] This is the first experimental proof of the superfluidity of both extraordinary phases of liquid ^{3}He. Fourth sound, a pressure wave in superfluid ^{4}He with normal fluid locked in a porous medium, was first discussed by Pellam[2] and observed by Rudnick and Shapiro.[3] It has been discussed theoretically in a context of ^{3}He by de Gennes[4] and Saslow.[5] Measurements of fourth-sound velocity C_4 yield relative superfluid density $\bar{\rho}_s/\rho$ via the equation

$$\bar{\rho}_s/\rho = C_4^2/C_1^2, \tag{1}$$

where C_1 is the velocity of first sound[6] and $\bar{\rho}_s/\rho$ denotes a suitable average if the superfluid is anisotropic or if size effects are important, and where thermal effects[3] have been neglected with sufficient accuracy for present purposes. Our measurements, extending down to $T/T_c \simeq 0.8$, show that $\bar{\rho}_s/\rho$ is quite small, varies slowly with temperature, and shows little or no detectable change near the first-order transition at T_{AB}; this is in possible disagreement with the interpretation of the wire-damping experiments[7] and with a prediction[8] relating $1-\rho_s/\rho$ and zero-sound velocity, but is reasonably close to what one might expect from susceptibility[9] measurements.

Our experimental epoxy cell, 2.63 cm long and 2.11 cm in diameter, was packed with cerium magnesium nitrate (CMN) powder (size less than 37 μm) to 80% of crystalline density, the CMN being used as superleak, refrigerant, and thermometer. Each end was closed using a capacitive-type pressure transducer.[3] For transient measurements a voltage step of 20–40 V was applied to the transmitting transducer; the receiving transducer was connected through a band-limiting amplifier to an oscilloscope. For resonance measurements the transmitter was driven by the reference channel of a lockin detector; the receiver was connected to a preamplifier