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Measurements of Brillouin-Backscatter Dependence on Density-Scale Lengths near Critical Density

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The Brillouin backscatter fraction was measured from laser-produced spherical plasmas with prepared scale lengths of from 5 to 50 μm. The scale lengths in the region of $0.1 \leqslant n/n_c \leqslant 1$ were measured using double-pulse holographic interferometry. The backscatter energy was found to vary from 5% to 25% of the incident energy over the range of scale lengths measured. The spectra of the backscatter light were obtained and show the red shifts characteristic of Brillouin scattering.

Most of the experiments in recent years of laser-plasma interactions with 1.06-μm light have shown rather small (~5%) fractions of stimulated Brillouin backscatter.[1] This has been due to the use of very short pulses of less than 100 psec, which lead to short density scale lengths. As the research in the field approaches the longer pulses of greater than 1 nsec, projected to be required for high-thermonuclear-yield experiments, one expects the stimulated Brillouin backscatter will become a serious energy-loss problem. The longer laser pulses can lead to longer density scale lengths in the underdense plasmas, thus creating conditions which are predicted to produce higher fractional stimulated backscatter. We have experimentally simulated these long scale lengths by irradiating spherical targets with a short laser pulse preceded by a controlled prepulse. The density profiles created by the prepulse have been measured by double-pulse holographic interferometry,[2,3] using a fourth harmonic (263 nm) probe beam with $f/2$ collection optics. The energy and spectral distribution of the backscattered light were also measured. We define backscatter as the light which is collected by the focusing lens.

The density region measured was the decade below critical density, i.e., $0.1 \leqslant n/n_c < 1.0$, where $n_c = 10^{21}$ cm^{-3}. Others[4,5] have examined the relationship between the backscattered energy and the density scale lengths in the more underdense region, near 10^{19} cm^{-3}. Although it was not possible to determine experimentally the density at which the scattering takes place, the following reasoning leads us to believe that Brillouin scattering is most likely to occur near densities of a few tenths of critical density. For a plasma with velocity and density gradients, the convective amplification[6,7] is proportional to $\omega_{pi}^2/(dK/dx)$, where K is the wave-number mismatch due to the gradients. Since these experiments were done on spherical targets, the velocity gradients in the underdense region are much lower than for plane targets, as a result of the divergence. Since the amplification is proportional to ω_{pi}^2, we expect the region of reflection to be at the highest density where modest density gradients exist. Profile steepening[8] may prevent stimulated backscatter from occurring at the highest densities; however, densities less than ~ $0.4n_c$ should be unaffected.[3] (By an analogous process, intense backscatter can self-limit by locally steepening the density profile[9]; this can occur more easily at lower densities.)

These experiments were conducted at intensities of up to 10^{16} W/cm^2, well above the threshold for Brillouin scattering indicated by the linear theory.[6] Therefore, the backscattered wave is expected to grow rapidly until limited by nonlinear effects, such as ion trapping[10] or wave breaking.[11] These effects cause the ions to heat, leading to strong Landau damping of the ion wave. Simulations[9,11] and analytic models[12,13] predict the largest variation in backscatter will occur as the effective plasma size is varied from several to approximately 100 vacuum wavelengths. We have attempted to investigate this parameter range, although we were unable to generate the longest scale lengths with the spherical mass-limited targets we used.

The targets, 65-μm-diam glass microballoons, were irradiated by two opposed circularly polarized beams at the University of Rochester's glass development laser (GDL) facility. The pulse width was 50 psec full width at half maximum, and the energy, focused on the center of the target through $f/2$ lenses, was typically 10 J. Prepulse energy was varied from 0 to 10% of the total laser energy, and the timing was varied from 0.6 to 2 nsec. For most of the data presented here, the prepulse was introduced 1.8 nsec before the main pulse. The backscatter spectra were recorded by a 1-m-Czerny-Turner spectrometer with a resolution, set by the slit width, of 1 Å. Calorimeters measured the energy of the incident and backscattered light. The holographic interferometer is similar to that used by Attwood *et al.*,[2,3] except for our 10-cm focal length $f/2$ collection lens. Also, we usually make our first (reference) exposure with the target already in place. This produces an image of the microballoon superimposed on the plasma fringes, but does not disturb the measurement so long as the fringes lie outside the original target. Should a fringe lie within the original target diameter [as occurred with some large (10%) prepulse shots] it cannot be easily interpreted. The probe beam was generated by splitting out a portion of the main laser beam, and passing it through successive doubling stages using type-II potassium dihydrogen phosphate (KDP) and type-I ammonium dihydrogen phosphate (ADP), respectively.[14] The ultraviolet diagnostic beam probed the plasma in a direction perpendicular to both the heating beams and the target support stalk. The latter was useful when focusing the holographic reconstruction during post-shot processing.[15] Figure 1(a) shows an interferogram of a shot with a small (0.2%) prepulse. For this shot, the peak of the probe beam arrived at the target during the peak of the heating pulse. Timing of the probe beam relative to the main laser was calibrated to within 10 psec with a streak camera looking at both the second

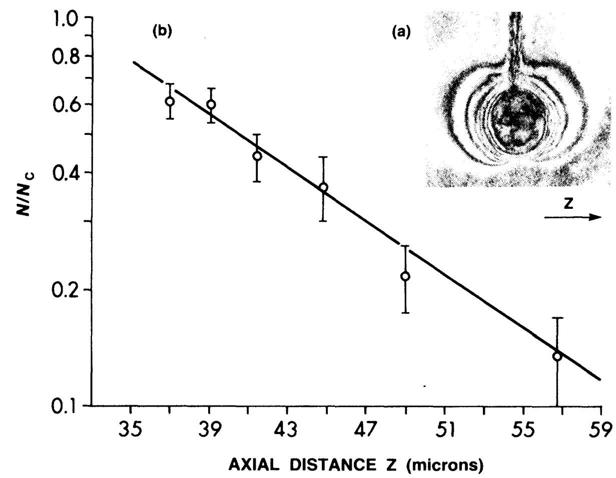

FIG. 1. (a) Holographic interferogram, showing original microballoon and interference fringes. (b) Axial density profile resulting from Abel inversion of (a). Distance is measured from the center of the target. Laser parameters were: 0.2% prepulse, $I = 5\times 10^{15}$ W/cm^2.

harmonic radiation generated by the target, and the residual green light in the probe beam. Figure 1(b) shows the axial density profile resulting from the Abel inversion of the fringes in 1(a). As a consequence of the large size of the plasma, and the resulting refraction,[15] the highest density measured in this interferogram is $\sim 0.6 n_c$.

The fraction of the incident energy backscattered is plotted against the density scale length created by the prepulse in Fig. 2. The scale length L is defined by the best fit of the density data with $n = n_0 \exp(-Z/L)$. The points shown in Fig. 2 are the results of probe measurements made at various times, from 0 up to 100 psec, before the peak of the heating pulse. The data were taken over an intensity range of 2 to 10 $\times 10^{15}$ W/cm^2. No correlation was observed between intensity and backscatter, which suggests saturation. We have compared this data with a model[12,13] which includes self-consistent ion heating and found reasonable agreement. In this model, indicated by the dashed line, L is the finite length of a homogeneous plasma. In the experiment, phase mismatching makes it unlikely that scattering occurs over the entire exponential scale length. Therefore, the data should be interpreted as supportive of the model's scaling, rather than the absolute value of the predicted backscatter.

Figure 3 shows the densitometer traces of the time-integrated backscatter spectra for two

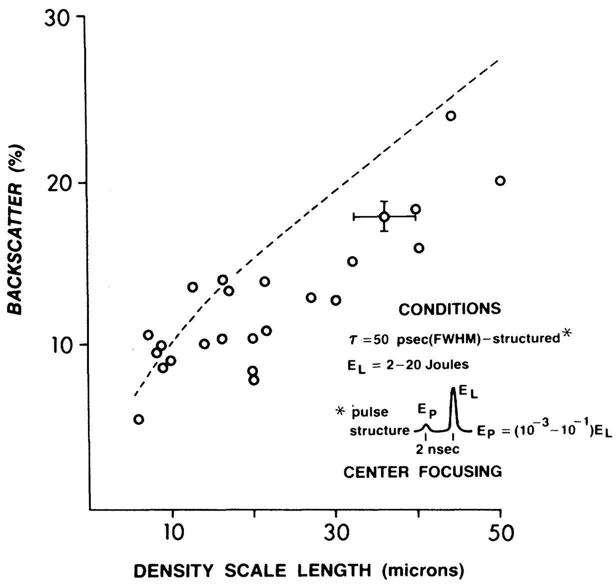

FIG. 2. Percent backscatter vs density scale length measured near critical density. The dashed line shows the predictions of a simple model (see Refs. 12 and 13).

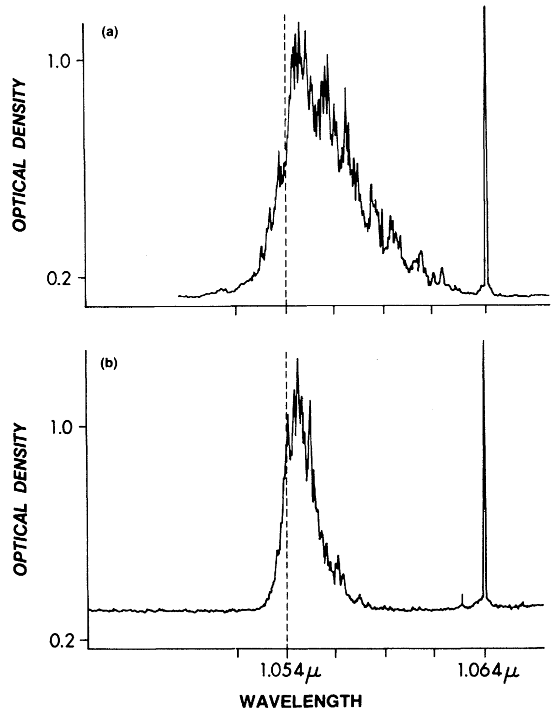

FIG. 3. Time-integrated backscatter spectra. (a) 3% prepulse, $I = 10^{16}$ W/cm^2, (b) 5% prepulse, $I = 8\times 10^{14}$ W/cm^2, defocused beams. The laser wavelength is indicated by the dotted line. The narrow feature at 1.064 μm is a reference mark. The axial density scale lengths were 22 μm for (a), and 24 μm for (b).

shots, both of which were preceded by a prepulse. The asymmetric red-shifted profile in Fig. 3(a) is typical of the data taken at high intensity (~ 10^{16} W/cm^2). Some of the backscattered energy has been red shifted 80 Å or more. This may be due to the existence of quasimodes[6,11]; for a sufficiently strong pump wave, the frequency of the ion wave can be shifted considerably beyond its usual normal mode. Another possibility is the coupling of higher-order ion modes with the incident pump wave.[11] At lower intensities, the spectrum is still red shifted, but more symmetric. Figure 3(b) shows the backscatter spectrum of a shot with an intensity of ~ 10^{15} W/cm^2. It should be noted that the reduction in intensity was accomplished by defocusing the beams.

In summary, we have presented data showing Brillouin backscatter from spherical targets as a function of the density scale length, where the density was measured over the range $0.1 \leq n/n_c \leq 0.8$. We have noted that our data is in agreement with a simple analytic model.[12,13] We have also presented backscatter spectra, showing red shifts, and noted a qualitative change in the spectra for defocused lower-intensity illumination.

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Dynamic Scaling of Ultrasonic Attenuation at the Liquid Helium λ Point

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We present a new approach to the ultrasonic attenuation in liquid helium, based on the Pippard-Buckingham-Fairbanks relations. An appropriate frequency-dependent generalization yields a theory with no adjustable parameters, in good agreement with experiment.

In spite of many detailed and extensive experimental studies[1-5] of the ultrasonic attenuation at the λ point of liquid helium there does not yet exist a satisfactory theory of this interesting critical phenomenon. The purpose of this note is to provide such a theory. The numerous theoretical contributions to this subject,[6-9] although failing to provide a definitive theory, have suggested some useful qualitative ideas which have been helpful to the experimentalists in attempting to fit their data phenomenologically. With the increasing accuracy and range of the measurements this approach has become, however, less than satisfactory. The exponent $1+y$ describing the dependence of the attenuation on frequency at the λ point has been found[1] to be significantly greater than 1. Furthermore, different values of y are needed for fitting the data in the low-[2] and high-frequency[1] ranges. We cite two more failures: (1) For temperatures T different from the λ-point value T_λ the data do not scale accurately[1,2] according to the reduced frequency variable $\Omega = \omega/\Gamma$, where ω is the angular frequency of the ultrasound and Γ is a T-dependent relaxation rate. (2) The "symmetrical" assumption for subtracting the fluctuation portion of the attenuation at $T < T_\lambda$ yields unphysical negative values[1] for the residual Landau-Khalatnikov[10] portion. There is clearly a need for a reliable theory which can serve as a guide for further exploration of the attenuation of ultrasound in liquid helium.

We start with the thermodynamic expression for the isentropic compressibility of liquid helium in the vicinity of the λ point,

$$\beta_S = \beta_T - \frac{T\alpha_T^{\,2}}{C_P} = \text{const} + \frac{\text{const}}{C_P}, \tag{1}$$

where α_T, β_T, and C_P are the thermal expansion coefficient, the isothermal compressibility, and the specific heat at constant pressure, respectively. The final form of Eq. (1) is an approximation that holds in the immediate vicinity of the λ point. It follows from the Pippard-Buckingham-Fairbank relations and results from the fact that α_T, β_T, and C_P all have the same asymptotic

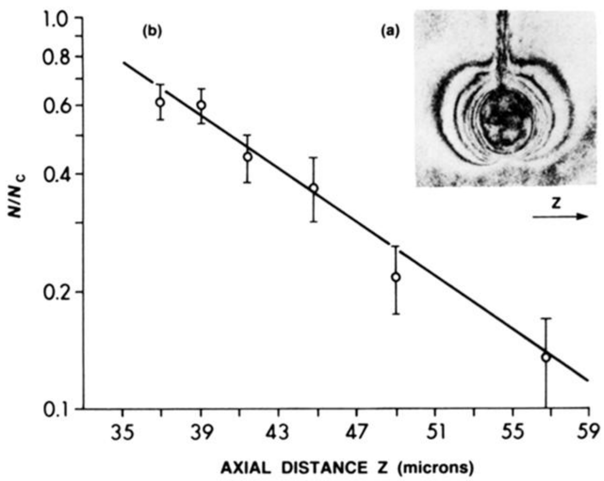

FIG. 1. (a) Holographic interferogram, showing original microballoon and interference fringes. (b) Axial density profile resulting from Abel inversion of (a). Distance is measured from the center of the target. Laser parameters were: 0.2% prepulse, $I = 5\times 10^{15}$ W/cm^2.