treatment of SHG, which should be applicable also to the DFG case, is that the initially degenerate magnetic sublevels are mixed by the external magnetic field. The mixing of hyperfine split levels is of secondary importance. The example of calcium is important in this respect.

[1]R. W. Terhune, P. Maker, and C. M. Savage, Phys. Rev. Lett. 8, 21 (1962).
[2]J. A. Giordmaine, in *Quantum Electronics, Proceedings of the Third International Congress, Paris, 1963*, edited by P. Givet and N. Bloembergen (Columbia Univ. Press, New York, 1964), p. 1549.
[3]F. Brown, R. E. Parks, and A. M. Sleeper, Phys. Rev. Lett. 14, 1029 (1965).
[4]N. Bloembergen, R. K. Chang, and C. H. Lee, Phys. Rev. Lett. 16, 986 (1966); N. Bloembergen, R. K. Chang, S. S. Jha, and C. H. Lee, Phys. Rev. 174, 813 (1968).
[5]F. Brown and M. Matsuoka, Phys. Rev. 185, 985 (1969).
[6]D. S. Bethune, R. W. Smith, and Y. R. Shen, Phys. Rev. Lett. 37, 431 (1976).
[7]T. Hänsch and P. Toschek, Z. Phys. 236, 373 (1970).
[8]M. Matsuoka, H. Nakatsuka, and J. Okada, Phys. Rev. A 12, 1602 (1975).
[9]E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra* (Cambridge Univ. Press, Cambridge, England, 1964), p. 95.
[10]P. S. Pershan, Phys. Rev. 130, 919 (1963).
[11]C. E. Tull, M. Jackson, R. P. McEachran, and M. Cohen, Can. J. Phys. 50, 1169 (1972).
[12]The signal shows a saturation near the density of 10^{15} cm^{-3}. The most probable reason for this is the depletion of the excitation by a strong resonant cascade emission. [H. Nakatsuka, J. Okada, and M. Matsuoka, J. Phys. Soc. Jpn. 37, 1406 (1974)].

Evidence of Parametric Decay and Brillouin Backscatter Excited by a CO_2 Laser

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Experimental measurements of the scattered infrared emission in the vicinity of 10 μm are presented. The shape and power dependence of the backscattered spectrum indicates the presence of the Brillouin backscatter instability. The sidebands on the side-scattered radiation are found to be strongest for emission perpendicular to the electric field vector of the incident radiation. This is interpreted as being the result of the parametric decay instability.

The interaction of high-power laser radiation with plasmas is of current interest because of possible use of such lasers in thermonuclear fusion. The absorption or reflection mechanisms, that are important aspects of laser-target interactions, have generated a considerable number of theoretical papers. Experimentally, the existence of nonlinear effects in plasmas has be surmised from plasma emission at $\frac{3}{2}$ and 2 times the 1.06-μm frequency of glass lasers and at second and third harmonics for CO_2.[1-6] Although studied in considerable detail in the interaction of microwaves with plasma,[7,8] this is the first experiment that shows convincing evidence of the parametric decay instability in laser produced plasma. Elegant evidence of stimulated backscatter has been obtained by Ripin *et al.*,[9] as determined by the rapid rise and directional properties of the reflected radiation. We also present new measurements on the existence and effect of the Brillouin backscatter instability.

The CO_2 laser used in these experiments consisted of a mode-locked oscillator, optical gate, and four stages of amplification.[10] It produced 5 J in a 1.5-ns pulse. The laser beam was focused by an off-axis parabolic mirror, equivalent to $f/2$ optics, to fluxes up to 10^{13} W/cm^2. The scattered spectra was obtained with a 1-m grating spectrograph and a HgCdTe detector with a rise time of 1 ns. A schematic of the experimental setup is shown in Fig. 1. The target consisted of a ribbon of 150-μm-thick polyethylene. In order to ensure that the spectral structure observed was not inherent to the laser beam, the wavelength spectra of the incident laser beam and that of the scattered signal were taken simultaneously on several runs. It should be pointed out that the spectra presented were taken on a shot-to-shot basis and that the signal was time-integrated during the CO_2 laser pulse (the rise time of the detector is about equal to the laser pulse length).

Results of the backscatter experiments are shown in Fig. 2. Although a similar spectrum

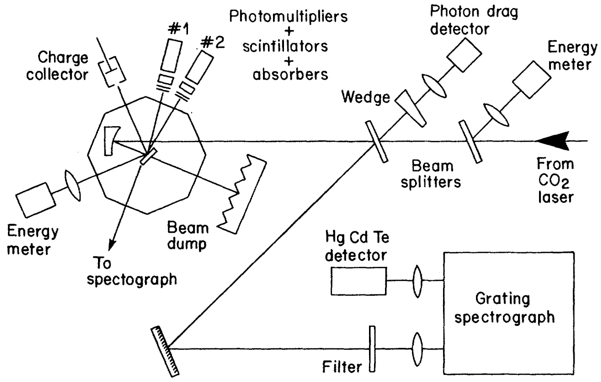

FIG. 1. Schematic of experimental setup.

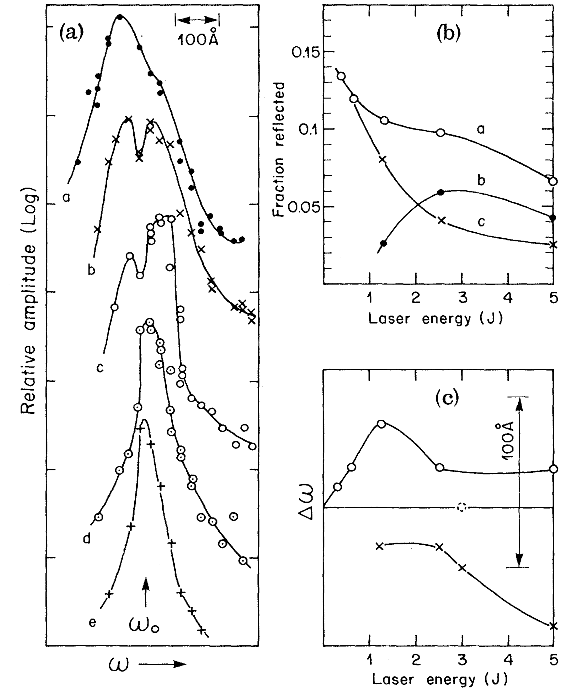

FIG. 2. Backscattered emission spectra as a function of laser power for polyethylene targets. (a) The curves are for laser energies of 5 J for curve *a*; 2.5 J for curve *b*; 1.25 J for curve *c*; 0.63 J for curve *d*; and 0.31 J for curve *e*. Each of the curves was down-shifted by one order of magnitude from the previous one for clarity. (b) The fraction of the laser energy backscattered as a function of laser energy. Curve *a* is the total fractional backscattered energy whereas curves *b* and *c* represent the energy contained in the red- and blue-shifted components, respectively. (c) The frequency shift of the two backscattered components as a function of laser energy. For all these graphs 5 J corresponds to a flux of 10^{13} W/cm^2. ω_0 is the frequency of the incident laser beam.

has been reported for a CO_2 laser, no detailed dependence of the spectral shape on laser power was presented.[11] The backscattered radiation was collected and recollimated by the focusing mirror as shown in Fig. 1. For laser powers below 10^{12} W/cm^2 [Fig. 2(a), curves *e* and *d*] we observe a blue shift and a broadening in the backscattered light as reported previously.[12] This is attributed to a Doppler-shifted reflection from the critical layer, that has been broadened as the result of microturbulence induced by the laser. A novel aspect of the backscattered light is the splitting of the spectrum that is observed for laser fluxes in the vicinity of 5×10^{12} W/cm^2 [Fig. 2(a), curve *c*]. Assuming a scale length of 100 μm and using a measured electron temperature[13] of 200–300 eV, as obtain[14] an inhomogeneous threshold of about 2×10^{12} W/cm^2 for the Brillouin backscatter instability, a number in relatively good agreement with the measured laser flux. As the laser power is further increased, the red component of the backscattered light increases and finally dominates the spectrum at powers of 10^{13} W/cm^2 [Fig. 2(a), curve *a*]. This rapid relative increase of the red component with the incident flux and the threshold behavior are strong arguments for identifying this behavior as stimulated Brillouin scattering. In Fig. 2(b) we have plotted the fractional reflected energy as a function of laser energy. Although the backscattered energy monotonically increases with laser power the percentage reflected actually decreases (curve *a*). For low powers, the classical, blue-shifted component (curve *c*) is responsible for the bulk of the reflection, whereas at higher energies it is the red or Brillouin component (curve *b*) that dominates.

In Fig. 2(c) we show the frequency shift in both backscattered components as a function of laser energy. For low energies we find that the blue shift increases linearly with laser energy until the red component appears. The blue shift then decreases and stabilizes at a value of about 20 Å. The broken circle in Fig. 2(c) was obtained from an experiment where two pulses separated by 23 ns[13] were sent on the target. For this case we found an unshifted component and a red component in the backscattered spectra. The unshifted component may be interpreted as the classical reflection from a quasistationary plasma created by the first pulse, whereas the red-shifted component is the expected Brillouin backscatter. The dependence of the red shift on laser energy may be used as an argument in eliminating another momentum-absorbing mechanism, stimulated Compton scattering. Stimulated Compton scattering should provide a red shift that would be primarily dependent on the plasma temperature which was, however, not found to vary considerably over the range of interest.[13] The behavior of the red shift with power may, however, be explained by once again assuming that Brillouin backscatter is the dominant mechanism.

The frequency shift ($\Delta\omega$) is given by[15] $\Delta\omega/\omega = 2\eta v_{\mathrm{IA}}/c$, where η is the index of refraction of the plasma, v_{IA} the ion acoustic velocity, and c the speed of light. As the threshold for Brillouin backscatter is lower for denser and hotter plasmas, assuming classical damping for the photons, it is expected that at low power the interactions occur near the critical density layer where $\eta \to 0$, whereas at higher powers it may occur at lower densities where $\eta \to 1$ ($\Delta\lambda \sim 80$ Å), thus increasing the observed wavelength shift.

We have also observed infrared emission, whose wavelength differed by as much as 10^3 Å from the incident laser radiation. Such large wavelength shifts cannot be accounted for by stimulated Brillouin scattering, as this would require electron temperatures about one hundred times higher than measured. Such large frequency shifts, may however be expected from parametric decay as already observed in many microwave experiments.[7] The decay products are electrostatic waves that couple to electromagnetic waves in inhomogeneous plasmas. However as a consequence of the large difference in the phase velocities of longitudinal plasma waves and electromagnetic waves in vacuum, the propagation direction of the electromagnetic waves is primarily in a direction perpendicular to the propagation vector of the electrostatic waves.[16,17] Furthermore, the ion acoustic waves that are expected to be excited will have wavelengths of the order of several Debye lengths or frequencies that are about a half to a fifth of the ion plasma frequency. This will correspond to frequency shifts of the excited electron-plasma wave of the order of 3×10^{11} Hz or a wavelength shift of about 10^3 Å in any electromagnetic waves that could be generated by the unstable electrostatic wave. A result of a search for such sidebands on the backscattered signal is shown in Fig. 3(e). A sideband on the red side of the main backscattered peak does indeed exist. The sideband is located about 300 Å from the main peak. There is also a somewhat weaker shoulder which extends up to 800 Å from the main peak. This spectrum is similar to that obtained in the study of parametric decay generated by microwaves.[8]

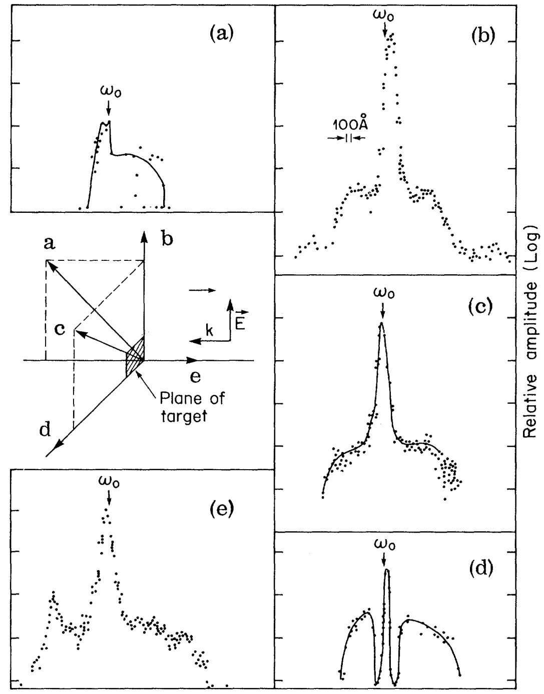

FIG. 3. Spectrum of side-scattered radiation at various angles with respect to the polarization of the laser beam. The laser energy was about 5 J with a flux of about 10^{13} W/cm^2. The target material was polyethylene.

In Fig. 3 we show the infrared emission spectra for various angles with respect to the laser beam. We find that the sidebands are strongest in a direction perpendicular to the electric field vector of the incident laser beam [Fig. 3(d)], where they are about one order of magnitude lower than the main peak. At an angle of 45° with respect to the electric field vector, the sidebands are considerably lower and are now more than two orders of magnitude below the main peak. In the direction along the electric field vector [Fig. 3(b)] the sidebands are nearly four orders of magnitude below the main peak. This angular dependence of the sideband structure may be explained by the fact that the parametric decay instability has its lowest threshold for electrostatic waves that propagate in a direction nearly parallel to the electric field of the driving wave. Since these electrostatic waves will radiate electromagnetic waves in a direction perpendicular to their wave vectors, the sidebands should be strongest in a plane perpendicular to the electric field vector of the incident laser radiation. We cannot, however, for the moment explain the curious spectrum observed in Fig. 3(a) (45° to both the wave vector and electric field vector of the laser beam), and a more detailed study is now being undertaken.

In conclusion, we have presented the first evidence of the parametric decay instability and a detailed study of the evolution of the backscattered spectrum with laser power. From a study of the threshold, frequency shift, and dependence on laser power we identify the red-shifted component of the backscattered spectrum as being due to the stimulated Brillouin backscatter instability. We find, for powers above 5×10^{12} W/cm^2, that stimulated Brillouin is the dominant reflection mechanism. However, the fraction of laser energy reflected as a result of this instability is a maximum for a laser flux of 5×10^{12} W/cm^2 and slowly decreases for higher powers. The sidebands in the side-scattered radiation were strongest for emission perpendicular to polarization vector of the laser beam. This angular dependence and the magnitude of the wavelength shifts are both measurements that strongly support the interpretation of the sidebands as being due to the electromagnetic leakage of electrostatic waves generated through parametric decay.

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[1]J. L. Bobin, M. Decroisette, B. Meyer, and Y. Vitel, Phys. Rev. Lett. 30, 37 (1973).

[2]Ping Lee, D. V. Giovanelli, R. P. Godwin, and G. H. McCall, Appl. Phys. Lett. 24, 406 (1974).

[3]C. Yamanaka, T. Yamanaka, T. Sasaki, J. Mizui, and H. B. Kang, Phys. Rev. Lett. 32, 1038 (1974).

[4]K. Eidmann and R. Sigel, Phys. Rev. Lett. 34, 799 (1975).

[5]E. B. Goldman, in Proceedings of the Second Conference on Plasma Science, Ann Arbor, Michigan, 1975 (unpublished), paper 6A.

[6]E. Fabre, L. Popovics, C. Stenz, and J. Virmont, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Thermonuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975).

[7]M. Porkolab, in *Proceedings of the Twelfth International Conference on Phenomena in Ionized Gases, Eindhoven, The Netherlands, 1975,* edited by J. G. A. Hölscher (North-Holland, Amsterdam, 1976), Pt. 2, p. 86, and references therein.

[8]M. Porkolab, V. Arunasalam, N. Luhmann, Jr., and J. P. M. Schmitt, Nucl. Fusion 16, 269 (1976).

[9]B. H. Ripin, J. M. McMahon, E. A. McLean, M. W. Manheimer, and J. A. Stamper, Phys. Rev. Lett. 33, 634 (1974).

[10]F. Rheault, J. L. Lachambre, P. Lavigne, H. Pépin, and H. A. Baldis, Rev. Sci. Instrum. 46, 1244 (1975).

[11]K. B. Mitchell, T. F. Stratton, and P. B. Weiss, Appl. Phys. Lett. 27, 11 (1975).

[12]H. A. Baldis, H. Pépin, and T. W. Johnston, Opt. Commun. 4, 311 (1975).

[13]B. Grek, H. Pépin, T. W. Johnston, J. N. Leboeuf, and H. A. Baldi, to be published.

[14]C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

[15]L. M. Goldman, J. Sovres, and M. Lubin, Phys. Rev. Lett. 31, 1184 (1973).

[16]M. Fuse and S. Ichimaru, J. Phys. Jpn. 40, 830 (1976).

[17]D. Tidman and G. M. Weiss, Phys. Fluids 4, 703 (1961).