etc. These are in fact the values for the Maxwell model and they agree with the results of Wang-Chang and Uhlenbeck. For a $1/r^s$ repulsive potential, the coefficients are temperature independent, and they are slowly increasing functions of the force index s, differing from the values (6) by less than 10% for $s=\infty$ (hard-sphere model). For a Lennard-Jones (12-6) potential, the coefficients are weakly temperature dependent but the deviations from (6) are never more than 7%. This insensitivity to the intermolecular potential makes a significant comparison with experiment possible, especially since the correct values of a_1 and b_2 are considerably different from the Navier-Stokes values (3).

In Figs. 1 and 2, the experimental values[3] for the initial frequency dependence of U and for the deviation from the first (Kirchhoff) value of the absorption coefficient in neon are plotted against ξ^2. The lines labeled Burnett and Super-Burnett refer to the values (6); they clearly represent the initial slope of the experimental curves much better than the Navier-Stokes values (3).

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[1]C. S. Wang-Chang and G. E. Uhlenbeck, Report of the Engineering Research Institute, University of Michigan, 1952. This report will be reprinted in Studies in Statistical Mechanics (North-Holland Publishing Company, Amsterdam, The Netherlands, to be published), Vol. IV.

[2]See J. Foch, dissertation, Rockefeller University, 1967 (unpublished). Parts of this dissertation will be incorporated in an article by G. W. Ford and J. Foch on the propagation of sound which will also appear in Studies in Statistical Mechanics (North-Holland Publishing Company, Amsterdam, The Netherlands, to be published), Vol. IV.

[3]M. Greenspan, J. Acoust. Soc. Am. 28, 644 (1956). We are indebted to Dr. Greenspan for sending us tables of the original data on which Figs. 1 and 2 are based.

OBSERVATION OF ANOMALOUS ELECTRON HEATING IN PLASMA SHOCK WAVES*

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Direct observations are reported of the electron velocity distribution throughout the region traversed by a magnetic shock wave in a plasma. In one case, the electron heating rate is greater than 10 times that predicted from normal and compressional effects.

In ordinary magnetohydrodynamic shock waves, known resistive (electron-ion collisions) and viscous (ion-ion collisions) processes account for the dissipation of the initial shock-frame streaming energy. In low-density plasmas such binary collision processes may be unable to provide the dissipation, and a form of anomalous dissipation due to collective plasma interactions takes over. We report here measurements that show the occurence of such anomalous dissipation.

A technique for obtaining electron velocity distributions, and hence heating rates, is the analysis of light scattered from the plasma when it has been illuminated by an intense source. The source used is a 200-MW Q-spoiled ruby laser, focused into the plasma to probe a small (~1 mm^3) volume with 20-nsec time resolution. Spectral analysis of the scattered light yields the one-dimensional electron velocity distribution in a direction defined by the difference between the wave vectors of the incident and scattered light. The electron density profile through the shock follows from the area under the scattered light profiles.

Scattering measurements were made on the nonlinear compressional waves produced in an electrodeless discharge tube. Results of magnetic-probe and emission-spectroscopic investigations of waves in this device have been reported.[1] A large-amplitude, radially converging compressional wave is induced in a previously formed plasma by a rapidly rising current flowing in a wide, single-turn strap wrapped around a 10-cm-diam quartz tube. The laser beam is parallel to, and 1.8 cm off, the axis. Scattered light collected at 90° to the incident beam direction is analyzed by tunable interference filters.

In operation, the laser is pulsed on as the shock passes over the laser focal region. Successive shots are timed so as to allow a picture to be built up of the spectral changes in scattered light as the shock traverses the illuminated region.

Typically the compressional waves do not reach a steady state in the short path (5 cm) available; so predictions of temperature and density using the DeHoffmann-Teller equilibrium shock relations may only be applied with caution. In all cases, the measured compression ratios were high, and measured temperature ratios agreed to within a factor of 3 with these predictions. We have taken the phenomenological approach of comparing the observed electron temperatures with those calculated from a model including resistive and compressional heating and using the observed current density and plasma density. The perpendicular resistivity given by Spitzer[2] is used in this calculation, which is made step by step through the front, computing at each step the temperature increase appropriate to the parameters at that point. The computations assume a steady state shock and ignore cylindrical convergence effects.

Two sets of observations were made with an initial magnetic "bias" field antiparallel to the main driving field. The initial plasma conditions for these two cases were similar, and differing results (strong electron heating in the tail of the distribution for one case) probably reflect a change between the two experiments in impurity content or in wall conditions that affect the initial formation of the current sheath.

In the first case, the initial conditions were $n_e = (3.7 \pm 0.3) \times 10^{14}$ cm^{-3}, $T_e = 1.3 \pm 0.2$ eV, bias field $B_{z0} = -510$ G. Application of the main driving field (about 6 kG) results in a compressional wave about 1 cm thick amplitude −2 kG running at 16 cm/μsec, corresponding to an Alfv̌en Mach number $M_A \simeq 2.8$. Viewed at the point where the laser is focused, this wave is preceded by a faster ($M_A \simeq 4$) low-amplitude ramp in magnetic field that rises linearly to about 300 G by the time the main compression begins. Following the main compression wave, the field rapidly reverses as the piston field arrives. The structure is similar to the two-sloped structures observed by Paul[3] and by Goldenbaum[1] for $M_A \gtrsim 2.7$.

Scattered-light profiles were determined from measurements at seven wavelengths covering about 150 Å. Most were taken with a two-channel analyzer, and within the limits of accuracy of the measurements, Gaussian profiles may be fitted to the points. In Fig. 1(a) we show time histories of magnetic field B_z as measured by a 1-mm-diam magnetic probe (positioned 1.8 cm from the tube axis, diametrically opposite the point where scattering measurements were made), electron density and temperature from scattered light profiles, and the computed temperature.

The electron density rises somewhat more slowly than does the magnetic field throughout the leading edge of the front. This lag occurs since a finite resistivity leads to some pene-

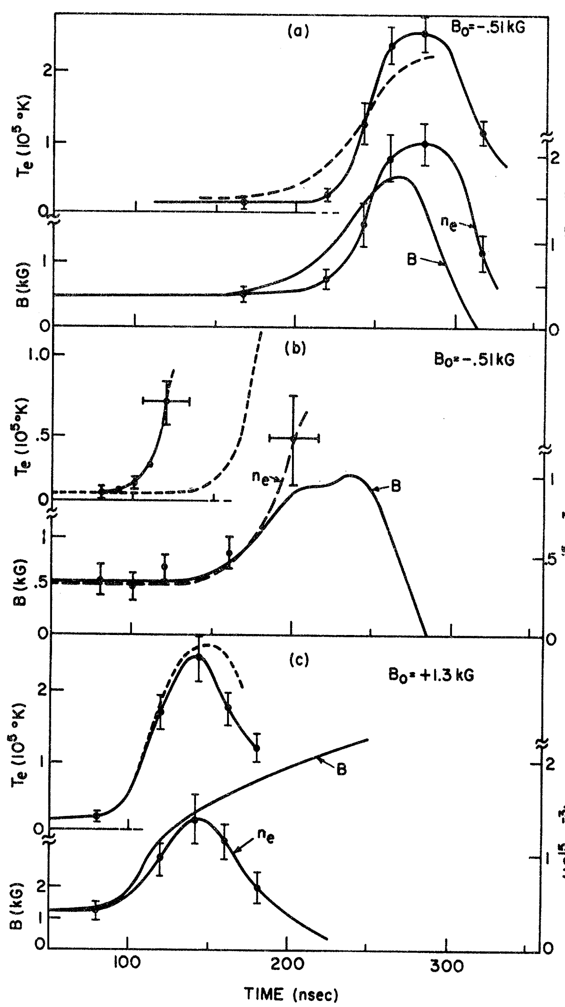

FIG. 1. Observed profiles of electron density, temperature, and magnetic field B_z through shock front for various initial conditions. Computed temperature is shown by dashed line.

tration of the plasma into the field. The observed penetration is consistent with that expected on the basis of the Spitzer resistivity. The measured temperature falls below computed temperature through much of the observed region, but probably not significantly. The presence of a small component of high-energy electrons would escape detection in the scattering measurements, being buried in the plasma continuum noise.

In the second case, the initial conditions were $N_e = (3.2 \pm 0.5) \times 10^{14}$ cm^{-3}, $T_e = 1.4 \pm 0.5$ eV, $B_{z0} = -510$ G. A similar gross magnetic structure, but with no detectable ramp, was observed in this case. The compressional wave travels about 12 cm/μsec ($M_A \simeq 2$) and is about 8 mm wide. The field compression ratio is about 3, considerably lower than in the first case but still higher than would be expected from a laminar shock theory with specific-heat ratio $\gamma = 2$.

Scattering profiles for this case are shown in Fig. 2. We see the first indication of change in the distribution function at about 100 nsec, about 30 nsec before the magnetic probe sees the first observable change in field. The spectral profile rapidly broadens, and by 150 nsec is beginning to show a marked departure from the Gaussian shape that would represent a Maxwellian distribution function. The far wings of the profile grow rapidly, with the result that by around 170 nsec the distribution appears to be that of a two-component plasma: a high-energy background of about 20-eV mean energy, containing about half the electrons, on which is superposed a low-temperature (1.5 eV) core. This distribution persists until about 200 nsec (where the main compressional feature has reached its peak), when it rapidly relaxes to a Maxwellian at about 20-eV temperature.

The relative timing of scattering and magnetic probe results is somewhat less certain in this case and may account for the fact that no lag [Fig. 1(b)] is observed between n_e and B. The "temperature" plotted is an average energy determined from the second moment of the observed distribution function. The heating rate deduced from the model calculations is at least an order of magnitude below the observed heating rate.

A discussion of some anomalous heating mechanisms will be found in Ref. 1. We find the observed current densities an order of magnitude too small to generate an electron two-stream

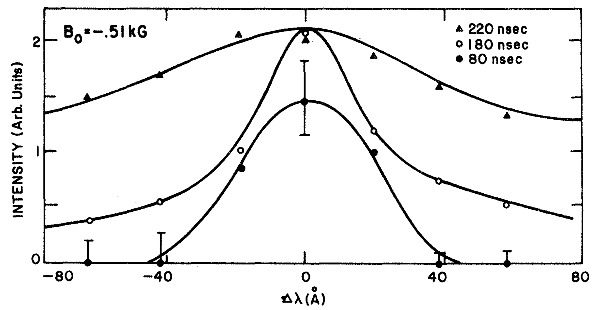

FIG. 2. Spectral profiles of scattered light through shock front.

instability. However, since our magnetic field measurements integrate magnetic fields with approximately 10-nsec time constant, it is possible that there exist local regions of high current density that are not resolved. In the current-sheath region, conditions may favor growth of an ion acoustic wave, which, propagating into the region in front of the shock, will be strongly damped at the interface where $T_e \simeq T_i$, thus providing a mechanism for diffusion of heat in front of the magnetic transition.

In the case of an initial parallel bias field of +1.3 kG, electron temperature of 1.3 ± 0.2 eV, and density of 3.7×10^{14} cm^{-3}, application of the driving-piston field produces a wave with its front moving at $M_A \simeq 1.3$. In this case there is no clear indication on the magnetic probe of a distinct shock front separated from a piston. Figure 1(c) shows the measured temperature, density, and magnetic field, as functions of time. The temperature as computed in previous cases is also plotted in Fig. 1(c). We see that here the computed temperature follows quite closely that observed, with no evidence of anomalous effects. The electron density is observed to decrease suddenly around 170 nsec, indicating the passage of the plasma-magnetic-field boundary.

In summary, for two of the cases studied, we find the observed heating to be fully accounted for by ordinary collisional heating plus adiabatic compression. In one case, heating occurred well in advance of the main current in the shock front, suggesting the heating has been taken over by some turbulent process on a scale not resolved by our measurements. Since the time for relaxation of the electron velocity distribution is around 10 nsec, the persistence of the non-Maxwellian distribution for about 50 nsec indicates that the anomalous heating process acts over a time of that order.

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[1]G. C. Goldenbaum, to be published.

[2]L. Spitzer, The Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1962), 2nd ed.

[3]J. W. N. Paul et al., Nature 208, 133 (1965).

EVIDENCE OF PHONON ANNIHILATION PROCESSES IN THE EXCITED STATES OF $BaClF:Sm^{2+}$ †

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We have found direct evidence of upward, phonon annihilation, processes in the decay patterns of two metastable states $^5D_0$(14 542 cm^{-1}) and $^5D_1$(15 878 cm^{-1}) of $BaClF:Sm^{2+}$. Under pulse excitation, the decay curve of the $^5D_1$ fluorescence includes a long tail, with a time constant equal to the lifetime of $^5D_0$, which appears at ~280°K and grows in intensity with temperature; finally at ~400°K both states decay with the same time constant. This finding is consistent with the thermal dependence of the ratio of the intensities of the $^5D_1$ to the $^5D_0$ flourescence.

Consider a three-level fluorescent system with levels 1, 2, and 3, indicating, respectively, the ground state and two excited (metastable) states. Assume also that the system can be optically excited by pumping into an absorption band above level 3 and that the excited centers decay from this band to level 3 by very fast radiationless processes. When excited by a sharp pulse of light, the population of level 2 decays to equilibrium according to an exponential law if the relaxation processes between the levels 3 and 2 are much faster than the lifetime of level 2. On the other hand, if the rate of these processes is of the same order of magnitude as the lifetime of level 2, the population decays according to a more complicated law which consists of the (algebraic) sum of two exponentials with characteristic time constants given by the lifetimes of levels 2 and 3. The fluorescence signal from level 2, after the end of the pulse, may present either a rise followed by an exponential decay or a double decay, the two conditions being determined by the values of the populations of levels 2 and 3 at the end of the pulse. The fluorescence signal from level 3 presents an exponential decay in any case.

If the two energy levels 2 and 3 are close enough, relaxation processes may take place among them with rates (for both the $3 \to 2$ and $2 \to 3$ processes) much faster than the intrinsic lifetimes of the two states, resulting in a "thermalized condition" for the two levels. In this condition the two levels decay to equilibrium with a common value for their decay constants, which depends on the intrinsic values of the two lifetimes, the degeneracies of the two levels, the energy gap, and the temperature.[1] Also, in this condition, if the system is under continuous optical excitation, the populations of the two levels and, consequently, the intensities of the fluorescence lines originating from them follow a Boltzmann law $e^{\Delta E/kT}$ with ΔE = energy gap. The existence of such a condition is generally mentioned as evidence of upward $(2 \to 3)$ phonon annihilation processes.

Considering now these upward (phonon annihilation) processes, it should be possible, in principle, to find direct evidence of them, in the form of a double exponential decay for the fluorescence from the upper fluorescent level 3, when their rate is comparable with the lifetime of this level. In these conditions one should be able to observe in the decaying fluorescence signal from level 3 an exponential component with time constant equal to the lifetime of level 2.

We have actually observed this phenomenon in the fluorescent system $BaClF:Sm^{2+}$. This system lends itself to these studies because the weak coupling of the fluorescent ion Sm^{2+} to the lattice allows the presence of three metastable states at low temperature: $^5D_0$ (14 542 cm^{-1}), $^5D_1$ (15 878 cm^{-1}), and $^5D_2$ (17 820 cm^{-1}). The fluorescence spectrum is due to transitions from these states to the ground-state multiplet $^7F_0$ to $^7F_4$ and is obtained by exciting the system in the strong $4f^55d$ bands. The energy level scheme along with the absorption bands is shown in Fig. 1.[2-4] All the fluorescence lines remain sharp even at very high temperatures (~10 cm^{-1} at 600°K).