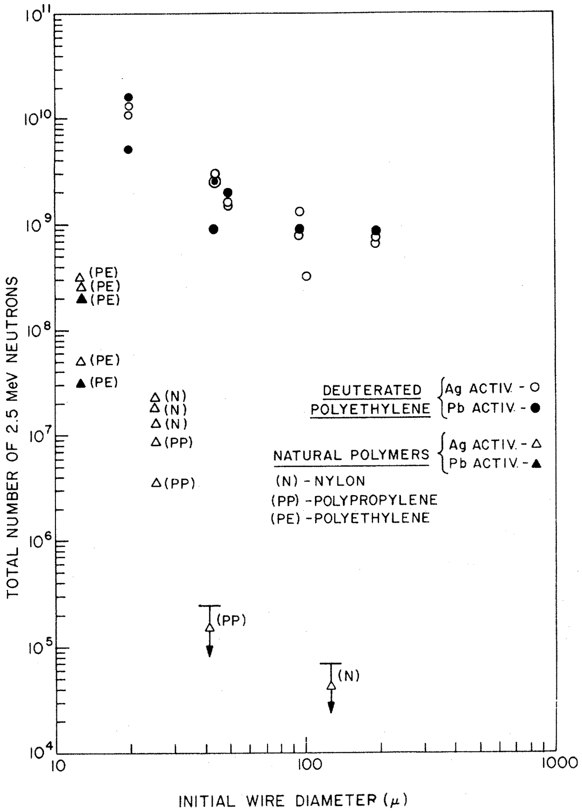

FIG. 1. Variation of neutron yield with initial fiber diameter.

all neutrons had 2.5-MeV energy.

The shape of the curves of yield versus diameter can be explained by simple pressure and energy balance considerations,[7] but it is difficult to understand the high neutron yield of the natural material. Also, the yields for the natural and deuterated material at the same diameter should be different by a factor of about 5×10^7 since the fusion reaction rate is proportional to the square of the deuteron density.

Extrapolation of the data for the deuterated material to small diameters using the scaling shown for the natural material indicates that neutron yields in excess of 10^{13} are attainable with deuterated fibers of about 10 μm diameter.

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Reasons for the Collisionless Nature of Interactions in a Laser-Produced Plasma Experiment*

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Experimental and theoretical evidence is presented to substantiate the collisionless nature of the interaction reported previously. We refute arguments claiming that the observed phenomena were collisional.

In a previous paper[1] we reported the observation of a collisionless momentum-transfer interaction between the ions of interstreaming plasmas in a laser-produced plasma experiment. The phenomenon is produced when a Q-switched laser is focused onto a small solid target and the resulting plasma expands radially outward through a low-density ambient plasma. Recently, Wright[2] has given arguments that collisional processes could explain our experimental results, claiming that the laser-produced plasma density at distances less than 2 cm from the target is high enough to collisionally snowplow the ambient.

The assumption was made in our original paper[1] that collisions were not important in the primary region of study (5–10 mm). The present paper deals with the reasons for that assumption and shows that all the available experimental evidence supports this assumption. We present in this paper (1) the key arguments, including energy conservation, which rule out the proposed collisional mechanism[2]; (2) a discussion of momentum-transfer mean free paths; (3) a discussion of how our experimental data are fitted by a collisionless, but not a collision-dominated, model; (4) additional experimental data confirming our original interpretation; and (5) comments on other relevant experiments.

There appears to be agreement on the fact that, in our experiment, a momentum-transfer interaction is occurring by which the laser-produced plasma, acting as a piston, sweeps up the ambient plasma. The proposed collisional model,[2] with which we disagree, is based on the assumption of an extremely high total number of laser-produced ions (9×10^{17}). This model is certainly ruled out by energy conservation. The model assumed that the *entire* mass in the focal region expands at a velocity of 2×10^{7} cm/sec (an assumption not in agreement with experimental data). This is equivalent to 200 J of kinetic energy, far in excess of the total energy available in the laser pulse.

Furthermore, in that collisional model[2] the plasma expands as a uniform sphere with a constant-density profile, according to $n(r)=n(0)(R_0/r)^3$, from an initial radius R_0, and initial solid density of $n(0)=1.1\times10^{23}$ cm^{-3}. It thus predicts an ion density at 1 cm of at least 10^{17} cm^{-3} in the interaction shell. We measured the thickness of this shell by two methods to be about 1.4 mm. At 1 cm total expansion radius this gives a volume of 1.8 cm^3 and hence the model predicts a total number of ions *in the shell* of 1.8×10^{17}. We measured the velocity of this expansion front by three different methods to be $\sim2\times10^{7}$ cm/sec. Thus, if the proposed model were correct, more than 40 J in absorbed laser energy would be required to account for the kinetic energy in the shell alone. There were only 8 J of laser energy available in the entire pulse in Fig. 1 of our original paper. Thus the calculation methods used to predict the collisional mechanism are not consistent with conservation of energy for the conditions of our experiment.

One can use energy conservation to place an upper limit on the ion density. Part of the laser energy is lost as radiation. A simple estimate of bremsstrahlung shows that it may equal 25% of the laser energy. Bound-free and bound-bound transitions are difficult to calculate but may represent an even greater energy loss. The remaining energy ($\sim50\%$) goes mainly into the kinetic energy of outward-streaming ions. Thus, for the case of 8 J incident laser energy (Fig. 1 of Ref. 1), the maximum number of ions which can be raised to a typical observed velocity (2×10^{7} cm/sec) is 6×10^{15}. At $r=1$ cm this gives an average density of 1.5×10^{15} cm^{-3}, which is 2 orders of magnitude lower than that computed by Wright.[2] This is consistent with our shadowgraphy studies, which showed that a significant part of the target within the focal region remains at the end of the laser pulse.

Our estimate that the laser-plasma density is comparable to the ambient density at 1 cm is consistent also with all our other experimental data. The density gradients in the interaction front were measured directly using shadowgraphy (Fig. 2 of Ref. 1) and the front thickness was measured by electric probes (Fig. 4 of Ref. 1). Let us assume, for the moment, that the laser-produced plasma density is high enough to collisionally snowplow the lower-density ambient plasma. If one has a piston of density 10^{17} cm^{-3} pushing on an ambient of density 10^{15} cm^{-3}, then the density gradients seen on the shadowgraphs would have been characteristic of the higher-density medium. The experimental evidence gives just the opposite result. We varied the ambient density from 5 to 100 mTorr, always finding that the density in the interaction region was approximately 10 times the ambient density of $10^{14}-10^{15}$ cm^{-3}. From the measured thickness of the front and the energy limitation on the number of laser-plasma ions, one can independently conclude that the shell density must be no more than about 1 order of magnitude greater than ambient density. Consequently, we conclude from both calculation and experiment that the high densities required for a collisional mechanism are not present in the interaction region.

We now turn to the question of the computation of momentum-transfer cross sections and momentum-transfer mean free paths. Wright[2] computed a momentum-transfer cross section of $\sim3\times10^{-17}$ cm^2 at a velocity of 2×10^{7} cm/sec from a semiempirical range-energy formula which had not been verified for the species and velocities found in our experiment. We have used cross sections which are only slightly lower, based on a screened Coulomb potential (screened by the atomic electrons), computed numerically by Everhart, Carbone, and Stone,[3] which have been verified experimentally in the range of interest.[4-7] However, we do not agree with the statement[2] that the actual cross section is probably an order of magnitude higher. An experiment was recently reported[8] which is directly relevant here. In that experiment, an aluminum plasma from a coaxial plasma gun freestreams more than 30 cm through photoionized air at a density of 3×10^{15} cm^{-3}. The reduced mass, ambient density, and relative velocity are comparable to our experimental values.

This experiment suggests a momentum-transfer cross section of $\leqslant 10^{-17}$ cm^2 at a velocity of 10^7 cm/sec. Thus we believe that the actual cross sections are in fair agreement with the theoretical values, rather than an order of magnitude higher.

At extremely small radii the laser plasma density is, of course, high enough to couple collisionally. Our reported observations were made primarily in the collisionless region (5–10 mm) and, as we have just shown, the ion densities at these radii are comparable to the ambient density. Consequently, we compute the momentum-transfer mean free path $\lambda = (n\sigma)^{-1}$ using 1 and 10 times the ambient density (pressure). The results are shown in Fig. 1. The dashed curve in Fig. 1 is based on the assumption of a density which is 10 times higher than the ambient density. This represents our estimate for the compression which takes place in the shell. We compare our experimental results with the mean free path λ_L in the lab frame. The λ_L is larger than the mean free path λ_c in the center-of-mass frame: $\lambda_L = (1 + m_1/m_a)\lambda_c$, where m_1 is the mass of the moving ion and m_a is the mass of the stationary ion.

Shock thicknesses in collisional plasmas are usually taken as 1 to several collisional mean free paths,[9] although the claim is made that it could be a fraction of this.[10] This, however, misses the point. The momentum-coupling region which we observe is not a shock. It is merely a region of momentum coupling between interstreaming plasmas. The mean free path is the e-folding distance for momentum coupling, so that several mean free paths are required for a high degree of coupling. We note from Fig. 1 that the mean free paths are several or many centimeters, i.e., larger than both the interaction-front thickness of 1–2 mm (Fig. 4 of Ref. 1) and the total expansion radius of 5–10 mm. Consequently, we do have collisionless conditions in our experiment.

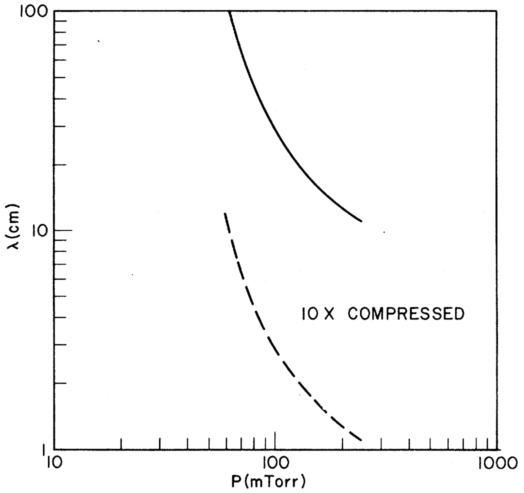

FIG. 1. Momentum-transfer mean free path in the laboratory frame for a C-N collision. Computation is made from $\lambda = (n\sigma)^{-1}$, where σ is computed using Ref. 3, taking into account the observed dependence of velocity on ambient pressure from Ref. 1. The proton-nitrogen mean free path is 1.8 times smaller.

In addition, our experimental results are not consistent with the usual collision-dominated model.[9] We measured the front thickness (δ) using electric probes. The thickness is given by $\delta = V\tau$, where V is the measured velocity of the front and τ is the rise time of the potential signal on the probe. We found that the rise time was independent of density at a fixed radial position. This means that the interaction thickness is independent of density except through the dependence of V on density. One would not expect this dependence from a collisional-coupling theory. However, a collisionless ion-ion, two-stream instability theory does predict precisely this dependence. We discussed this interpretation in detail in our previous paper.[1]

We made a considerable effort to perform secondary experiments to convince ourselves of the collisionless nature of the phenomena. Space did not permit us to report these results in our previous Letter.[1] Two experimental results are mentioned here. The question could be raised as to whether the multicomponent nature of our target was playing a role. (Our target was Lucite, which contains C, H, and O.) Consequently, we performed experiments using pure carbon filaments. As a result of these experiments we found that the presence of H and O in the target was inconsequential. The question could also be raised as to whether there would be any change if a lighter, monatomic gas were substituted for the heavier, diatomic nitrogen. Consequently, we performed experiments using He as the ambient gas. The basic phenomena were qualitatively unchanged. We present in Fig. 2 spectroscopic data showing momentum transfer to a He plasma. This figure should be compared to Fig. 4 of Ref. 1 for the N case.

The use of a pure C filament rules out the possibility that protons in the target, having a shorter mean free path, might be controlling the phenomena. The use of He does a similar thing; i.e., C streaming into He has a longer mean free path than C streaming into N. Thus even if we were

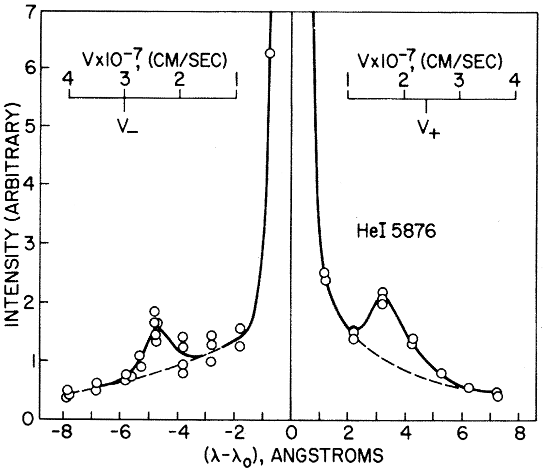

FIG. 2. Doppler-shifted satellite lines on the wings of the He I 5876 spectral line. Pressure, 200 mTorr He; observation distance, 8 mm from the target; time, 60 nsec after laser first strikes the Lucite-fiber target; spectrograph-slit function, 0.6 Å. The velocity scale at the top of the graph corresponds to particle velocities toward and away from the observer that would produce the corresponding spectral line shifts. The luminous front velocities measured with a streak camera are indicated as V_- and V_+, showing a slight asymmetry in the two directions.

to accept the mean free path of 2.7 mm computed on a collisional model[2] for streaming into N, we would then have to compute a mean free path of about 6 mm for He. Since this is far larger than the thickness of the shell, it again rules out the collisional mechanism.

There are many differences among the several experiments mentioned.[2] For example, an earlier publication of Koopman and Tidman[11] was performed at a lower velocity and may be in a different regime. The paper by Paul *et al.*[12] was a report of work in progress and the results were preliminary. Because of widely varying experimental conditions, comparisons with other experiments at this stage, while interesting, are nevertheless inconclusive.

The question of the role of binary collisions is always a very complicated one in plasma experiments. For example, electron-ion collisions may also play a role in momentum coupling. In our experiment, however, the electron temperature is high enough that ion-ion collisional effects are larger. There is still a need for more sophisticated theoretical treatments of collisional effects in plasmas.

We believe that the arguments presented here are actually very conservative. We have used a typical velocity of 2×10^7 cm/sec, averaged between 5 and 10 mm of expansion, in our estimates. Greater averaged velocities ($\sim4\times10^7$ cm/sec) were observed in some runs which also showed coupling to the ambient plasma. Moreover, the velocities have a radial dependence due to the detonation character of the front, so that higher velocities are expected at smaller radii. (Acceleration from thermal velocities occurs only in the submillimeter-size region where large pressure gradients exist.) These greater velocities imply smaller collisional cross sections and also place a more stringent condition (via energy conservation) on the upper limit of laser-plasma density.

In conclusion, we have given arguments, including energy conservation and experimental evidence, which invalidate a model[2] based on an unreasonably high total number of laser-produced ions. We have shown that there is internal consistency between our experimental data and our theoretical interpretation. We remain convinced of the correctness of our original assertion[1] that the observed interaction is collisionless.

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Nonexistence of Ion Acoustic Waves and Landau Damping Driven Electrostatically in an Ideal *Q* Machine*

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A computer was used to simulate ion acoustic wave generation by a grid. The self-consistent grid sheath and nonlinear effects were included. The experimentally observed wave propagation and Landau damping were reproduced quantitatively. Turning off the self-consistent electric field far from the grid left the "streaming" nature of the distribution function, the structure of the waves, and the magnitude of the damping essentially unchanged.

Comprehensive theory and experiments have been reported[1-15] on the propagation and collisionless damping of ion waves launched from a grid in a plasma of approximately equal ion and electron temperatures. The driving of waves by a negatively biased, oscillating potential applied to a grid inherently involves a nonlinear boundary value problem since a dynamic plasma sheath inherently forms about the electrodes. The sheath is nonlinear even for low excitation amplitudes since the bias and oscillating electric fields and the velocity gradient of the distribution function change very quickly. If the electric field were of some significance beyond the sheath, the solution would still be very nonlinear since our computer solutions demonstrate that gradients in velocity are very steep. As the potential well about a grid is made negative, ions are accelerated into the well and are trapped. As the potential is made more positive, the ions are released from the sheath at high kinetic energies. We call such escaping bursts of ions, that are little affected by the self-consistent electric field, pseudowaves. They resemble the free streaming electron phenomena responsible for klystron vacuum-tube operation.[16] We define genuine ion acoustic waves as propagating compressional oscillations which significantly involve all the ions in the locality of the wave (the ions thermally streaming in both the same and opposite directions of the wave) as well as the self-consistent electric field. Among various groups, definitions and semantics differ; but we use the definition that ion acoustic waves must have the self-consistent electric field to propagate and pseudowaves do not. Ion acoustic waves obey a dispersion relation derived from self-consistent kinetic theory.[1] If pseudowaves do seem to obey the dispersion relation, then it is because of the manner in which the waves are launched. Some linear theory suggests that the pseudowave (ballistic) solution is merely transitory and soon damps out while the acoustic (collective) solution dominates.[17] Our studies show that the opposite may occasionally be true. Nonlinear kinetic theory is needed to resolve the nature of the plasma disturbances (acoustic or pseudowave) generated by the time-varying potential on the grid.

To answer questions about the role of the self-consistent electric field, we have made a series of one-dimensional computer simulations of an equal-temperature, initially Maxwellian plasma about a transparent grid (also about an absorbing grid) with a negatively biased oscillating potential applied at frequencies $0.25f_{pi}$, $1f_{pi}$, $2f_{pi}$, and $5f_{pi}$, where f_{pi} is the ion plasma frequency in hertz. The fully nonlinear ion Vlasov-Poisson equations were solved with the electrons considered to be in isothermal equilibrium; that is, the electron density $n = n_0 \exp(e\varphi/T_e)$, where e is the electron charge, φ is the potential, and T_e is the electron temperature in eV. The boundary conditions at the ends far from the grid are that the input ions are half Maxwellian and that the output ions flow out self-consistently.

We also made a series of simulations with the same conditions as the lower frequency, fully self-consistent solutions except that for the phase-