finds $b_{\text{capture}}/a = 4.57 \times 10^{-2} E^{0.283}$.) All such calculations are invalid because all neglect the quantum frequency limitations.

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Evolution of Turbulent Electrostatic Shocks*

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Turbulent low–Mach-number electrostatic ion shocks are observed when ion reflections ahead of shocks are controlled by new methods. The spatial growth of the turbulence is mapped by a test-wave method and correlated with the distribution of reflected ions. Disagreements with computer experiments are explained.

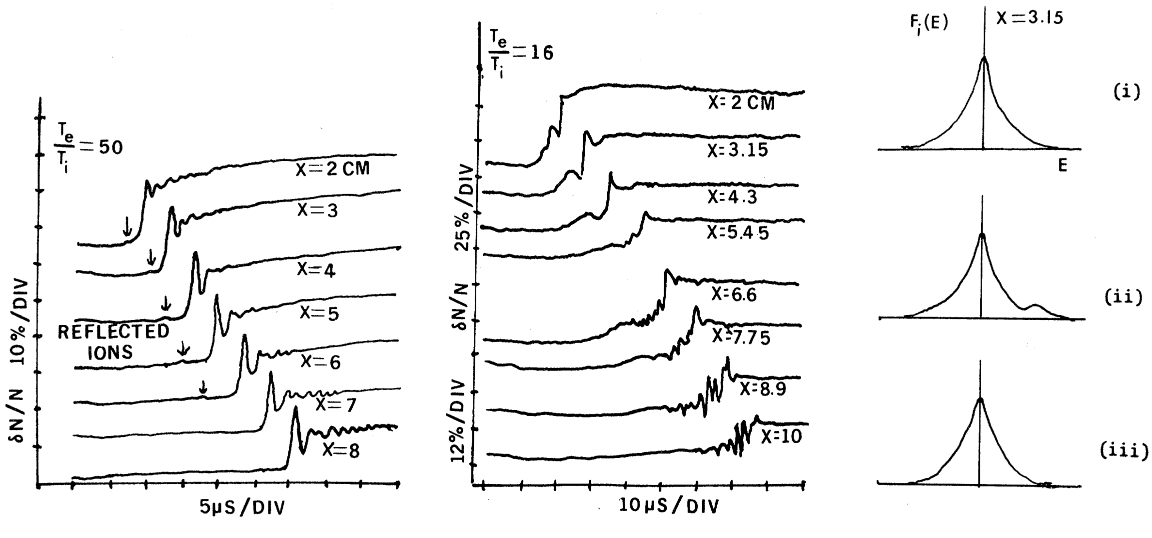
We wish to report controlled observations in the evolution of turbulent shocks from laminar shocks[1] due to the presence of reflected ions. Although such reflected ions have been predicted theoretically,[2] no conclusive experimental evidence has been reported which describes how turbulent shocks are generated by reflected ions in either magnetic or electrostatic shocks. The pulsed nature of past experiments[3,4] often made it difficult to measure microscopic quantities (such as distribution functions and the growth and decay of various Fourier components in the turbulent spectrum) which would have clarified the correlations between reflected ions and turbulence. The presence of a magnetic field further complicates the picture by permitting a much larger class of instabilities.

In our present experiments new methods of controlling the amount of reflected ions are used which keep all other plasma parameters constant. No magnetic field is imposed on the plasma and only ion acoustic waves are involved. Detailed measurement of each individual Fourier component in the turbulent spectrum by a test-wave technique revealed that the turbulence is ion acoustic in nature; the initial spatial growth rates of ion waves are correlated with the ion distribution functions measured by an energy analyzer *in situ* and the results can be understood qualitatively by a beam-plasma stability analysis. Our results differ considerably from those of a number of computer experiments[5-7] in which the assumption of one-dimensional nature could severely limit the growth of ion-wave turbulence.

We have employed two methods to create a large reflected ion beam: (1) operated at a relatively low electron-to-ion temperature ratio ($T_e/T_i \simeq 16$), such that there is a sufficient number of ions traveling near the shock velocity; (2) operated in an argon plasma with a small addition of helium at a high electron-to-ion temperature ratio,[8] $T_e/T_i \simeq 50$; the helium ions are the principal reflected component. The shocks are produced in the University of California, Los Angeles, double-plasma device which consists of cylindrical dc discharge plasmas produced in two chambers insulated from each other and separated by a grid with a mesh spacing less than the Debye length. The grid is biased negative so that the electrons in one plasma are isolated from the electrons in the other plasma while ions can flow from one plasma to the other. The plasma potential in each chamber can be varied by varying the wall potential. Shocks are produced by raising the plasma potential of the driver plasma above that of the target plasma by means of a linear voltage ramp applied to the wall of the driver plasma. The method of production is described more fully in Ref. 1.

Typical operating conditions are a neutral argon pressure of $\simeq 5\times10^{-4}$ Torr; a plasma density $N \simeq 10^9$ cm^{-3}; $1.0 < T_e < 5.0$ eV; and an ion temperature $T_i \simeq 0.1$ eV. The chamber dimensions are length = diam = 30 cm. The plasma is essentially collisionless for ion-acoustic wave phenomena.

(I) Shocks at different T_e/T_i.—Figure 1 shows the difference between a typical laminar shock at $T_e/T_i = 50$ and a typical turbulence shock when T_e/T_i is lowered to a value of 16. Both shocks can be described as laminar at $x = 2.0$ cm. (Distances are measured from the separation grid.) As the shocks propagate away from the formation region, small-amplitude oscillations are ob-



(a) (b) (c)

FIG. 1. (a) Propagating laminar shock in argon plasma with $T_e/T_i=50$ and few reflected ions. $N=8\times10^8$ cm^{-3}; $T_e=5.0$ eV; $M=1.15$; $T_i=0.1$ eV. (b) Propagating turbulent shock in argon plasma with $T_e/T_i=16$ and more reflected ions (~5%). $N=6.5\times10^8$ cm^{-3}; $T_e=1.6$ eV; $M=1.05$; $T_i=0.1$ eV. (c) Ion distribution function at $x=3.15$ cm: (i) before the shock arrives; (ii) at the reflected ion peak; (iii) after the shock. (Not to scale.)

served to develop into large-amplitude fluctuations in the transition region.

The rate of spatial growth can be estimated by a theory which considers the stability of an ion-beam–plasma system which approximates the situation just ahead of the shock. The dispersion relation considered by Fried and Wong[9] for a homogeneous beam-plasma system is

$$\epsilon(k,\omega)=1-\sum_\alpha\frac{\omega_\alpha^{\,2}}{k}\int\frac{dV}{kV-\omega}\,\frac{\partial f_\alpha(V)}{\partial V}=0, \qquad (1)$$

where species α has distribution $f_\alpha(V)$ and plasma frequency $\omega_\alpha=(4\pi N_\alpha q/M_\alpha)^{1/2}$. If Maxwellian distributions are assumed and we specialize to the case where the ions of the beam and the plasma have equal mass and temperature, we have

$$\frac{2k^2}{k_{\mathrm{D}i}^{\,2}}=Z'\frac{\omega}{ka_i}+\frac{N_b}{N}Z'\left(\frac{\omega}{ka_i}-\frac{V_b}{a_i}\right)-2\left(1+\frac{N_b}{N}\right)\frac{T_i}{T_e}, \qquad (2)$$

where V_b is the beam velocity, $a_i=(2T_i/M)^{1/2}$ is the ion thermal velocity, $k_{\mathrm{D}i}^{\,2}=4\pi Ne^2/T_i$, N_b is the beam density, and $Z'(s)$ is the derivative of the plasma dispersion function.[10] We have also assumed that the phase velocity ω/k is small compared to the electron thermal velocity. The Maxwellian assumption for the beam ions is much better in the case of light ions reflected from a heavy-ion shock since almost all light ions can be reflected. In the case of pure argon the distribution is more likely to be distorted. However, the present estimate suffices for a qualitative description.

By inserting in Eq. (2) the beam velocity $V_b/C_s=1.25$ [C_s is the ion acoustic wave speed, $\cong(T_e/M)^{1/2}$] and beam density $N_b/N=0.05$ as measured by an energy analyzer for the turbulent shock shown in Fig. 1(b), the maximum spatial growth rate $k_i/k_d=0.4\times10^{-2}$ is found for an optimum frequency $\omega/\omega_{pi}=0.6$. Experimentally the average growth rate of the turbulence is measured to be $k_i/k_d=0.2\times10^{-2}$ and the dominant ion fluctuation frequency is $\omega/\omega_{pi}=0.6\pm0.1$.

(II) Shocks with reflected light ions.—A new method of controlling the amount of reflected ions in the shock front and hence the degree of turbulence without changing other plasma parameters is accomplished in an argon plasma with a small amount of helium ions ($\simeq3\%$). The temperature ratio was maintained at the high value of 50 so that most of the reflected ions belonged to the lighter helium species and the turbulence could be switched on or off depending whether the helium ions were present or absent. In order to identify positively the nature of the turbulence, the wavelength and growth rates of the various Fourier components in the turbulent spectrum were measured by propagating a small-amplitude test wave of frequency ω ahead of the shock as

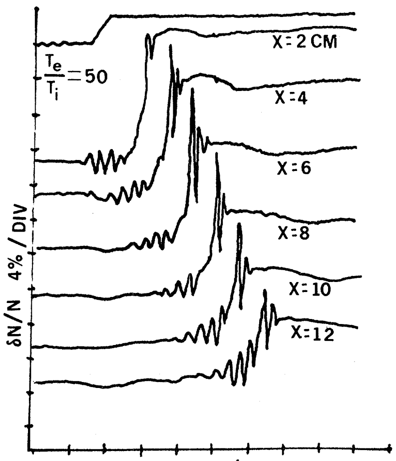


FIG. 2. Propagating shock in argon plasma with light ions added (~3% helium) which demonstrates the spatial growth of the injected test wave. The test wave first decays spatially because of linear damping but grows when the reflected beam overtakes the wave. $N=8.5\times10^8$ cm^{-3}; $T_e=5.0$ eV; $M=1.15$; $T_i=0.1$ eV.

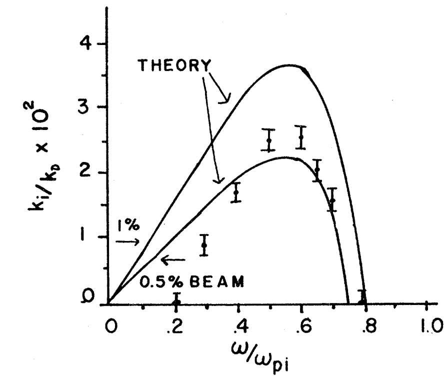


FIG. 3. Growth rate of Fourier components from linear theory and from experiments as done in Fig. 2. It was necessary to plot $\delta N_{\text{wave}}/\delta N_{\text{shock}}$ because both the wave and the shock decay with distance as a result of geometric effects and charge exchange ($l \cong 10$ cm for charge exchange).

shown in Fig. 2. As the shock overtakes the test wave, the reflected beam ahead of the shock enables the precursor wave to grow. The spatial growth rates of test waves of various frequencies are measured successively with relative ease and are plotted in Fig. 3. The velocity of the reflected helium beam was measured by an energy analyzer to be 1.15 times the shock velocity, instead of twice the speed of the shock as might be expected from a straightforward picture of reflection from a shock front in a one-dimension theory. One possible physical explanation is that the three-dimensional nature of the problem allows a beam to interact with ion acoustic waves at an angle even though $V_b > C_s$. Ion acoustic waves thus generated can scatter the particles, preventing them from reaching their final velocity of twice the shock speed.[11, 12]

There is good qualitative agreement between experiment and theory which uses the experimentally measured beam velocity and density in a form similar to Eq. (2), particularly with respect to the frequency of maximum growth rate. Theoretical results for both 0.5% and 1.0% beam density are presented in Fig. 3 to account for uncertainties in the beam densities. It is interesting to note that light ions have been shown to be effective at enhancing Landau damping of ion waves of small amplitude[13] ($e\varphi/T \ll 1$). However, when the ion wave has sufficiently large amplitude to reflect the light ions, as in the case of shock waves, these light ions amplify ion fluctuations by the mechanism of beam-plasma interaction.

(III) Broadening of the transition layer.—An estimate of the broadening can be obtained if the enhanced ion fluctuations are assumed to cause a local enhanced viscosity. In the fluid approximation of Moiseev and Sagdeev,[2] the ion equation of motion then becomes

$$Mn\frac{\partial v}{\partial t}+Mn\frac{\partial v}{\partial x}-\frac{\partial}{\partial x}\left(\frac{\eta}{2}\frac{\partial v}{\partial x}\right)=-en\frac{\partial \varphi}{\partial x}, \tag{3}$$

with the resulting Poisson equation,

$$\frac{d^2\varphi}{dx^2}=-4\pi e n_0\left[\left(1-\frac{2e\varphi}{MV_0^2}-\frac{\eta e(\partial\varphi/\partial x)}{M^2V_0^2N[V_0^2-(2e\varphi/M)]^{1/2}}\right)^{-1/2}-\exp(e\varphi/T_e)\right], \tag{4}$$

where the electrons are treated isothermally and the enhanced viscosity coefficient η is given by a quasilinear calculation similar to that done by Schmidt and Yoshikawa[14]: $\eta = C\langle e\varphi/T_e\rangle^2$. A computer solution of Eq. (4) gives a shock solution with the width of the transition layer increasing as the viscosity η is increased. This is in qualitative agreement with our observations. Measurements of the distribution functions shown in Fig. 1(c) also support this picture of wave-particle scattering.

(IV) Discussion and conclusions.—Tidman[15] has proposed a turbulent electrostatic shock mod-

el. The model consists of a high–Mach-number adiabatic shock with the turbulence driven by interpenetrating ion streams. The source of the stream in the Tidman model is the forward diffusion of hot subsonic gas behind the shock. Our experiment does not deal with this situation. The shocks discussed here have low Mach numbers, the electrons are isothermal, and the turbulence is driven by a beam of ions reflected from the shock front.

We would also like to distinguish between the turbulent shock reported here and the turbulent shocks studied in the magnetic-piston experiments.[3,4] The turbulence in the magnetic shocks is attributed to electron drift instabilities or cross-field instabilities. The inability of electrons to neutralize ion effects across the magnetic field makes the resulting ion waves quite different in character from the nonmagnetic case reported here and studied theoretically.

To our knowledge this is the first experiment which directly demonstrates the turbulence as arising from reflected ions and the broadening of the shock transition region as a consequence of turbulence. The absence of a magnetic field and the high T_e/T_i all bring this experiment closer to the regime of approximations underlying current nonlinear theories on saturation effects.

In the course of the experiment we have found that the simple linear stability theory not only gives a reasonable estimate of the spatial growth rates at small amplitudes (as expected) but also predicts the dominant frequency in the saturation spectrum as well. This prediction remains to be justified theoretically. On the other hand the absence of turbulence in one-dimensional computer experiments in contrast to the present laboratory observation does point to the need of a two-dimensional computer-simulation procedure in which the reflected ion beam can interact with ion acoustic waves at an angle. Finally the experimental techniques of controlling the reflected ions and the test-wave precursor method could find applications in other shock-wave experiments.

We wish to acknowledge stimulating discussions with Professor F. Coroniti, Professor B. D. Fried, Professor C. F. Kennel, Professor K. R. MacKenzie, Professor R. J. Taylor, and Professor R. White.

*Work supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)34, Project 157.

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