Observation of the effect of nonlinear thermal conductivity in a shock-wave front at velocities of 10^7–10^8 cm/sec

N. N. Zorev, G. V. Sklizkov, and A. S. Shikanov
P. N. Lebedev Physics Institute, USSR Academy of Sciences

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The structure of a shock-wave front at velocities of 10^7–10^8 cm/sec was investigated experimentally. The formation of a heated layer in front of a shock wave, which was produced by the action of electron thermal conductivity, was observed for the first time.

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Investigation of the structure of a shock front (SF) formed in a residual gas as a result of interaction of high-power laser radiation with high-temperature plasma,[1,2] is important not only in determining the parameters of the latter[3] but also presents an

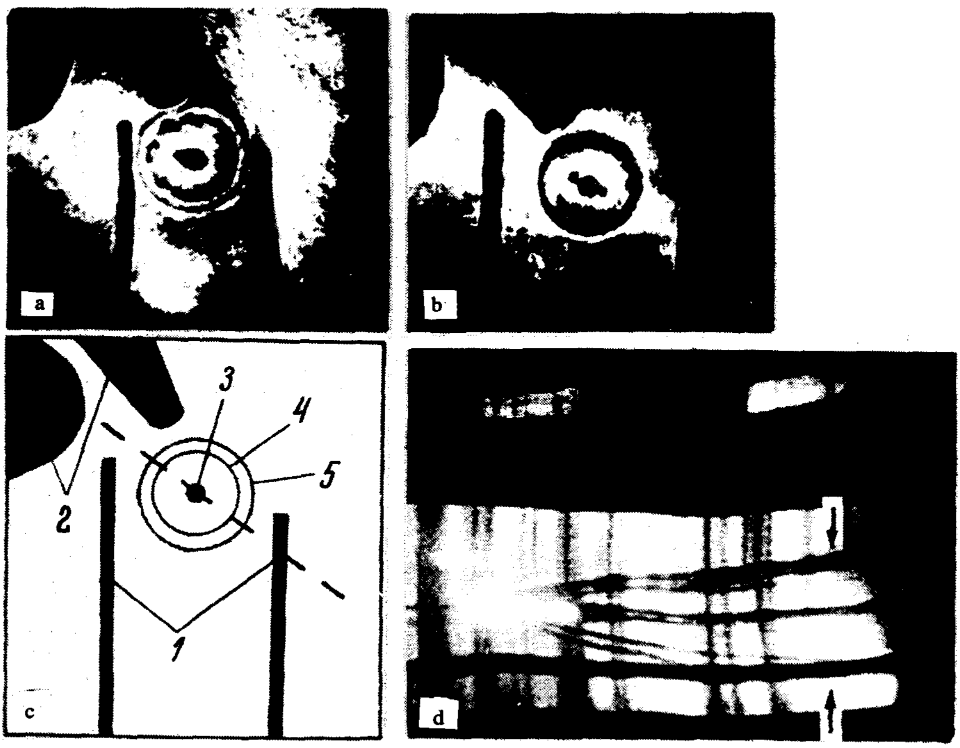

FIG. 1. Schlieren photographs of the shock wave: (a) frame photograph in deuterium; (b) frame photograph in the air; (c) a scheme illustrating the SW images: 1, target holder; 2, diagnostic equipment; 3, target plasma image; 4, "mass" front image of the SW; 5, ionization front. The broken line shows the location gap of the REP. (d) Slit scanning of the Schlieren image of the SW in deuterium. The upper part shows the sequence of the calibration pulses. The space and time scales are nonlinear. The arrows indicate the moment of exposure of the frame in Fig. 1a. All the photographs were obtained for $E_L \approx 150$ J, $\rho_1 = 2\times 10^{-6}$ g/cm^3; the target walls are made of ϕ 190-μm glass.

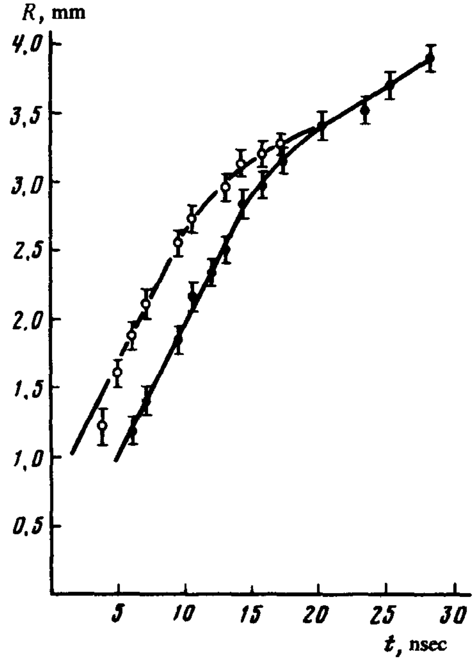

FIG. 2. R-t diagram plots the propagation of the shock wave (curve 1) and of the ionization front (curve 2) in the initial stage. $E_L = 60$ J, $\rho_1 = 4\times 10^{-6}$ g/cm^3; the target is made of ϕ 140-μm solid glass.

interest in itself. The point is that the initial velocity of the SF obtained in such experiments reaches several hundred kilometers per second, which is much higher than the values obtained for an SF by using the conventional methods under laboratory conditions. The structure of the front of strong SF with velocities of $\sim 10^7$–10^8 cm/sec has been investigated theoretically in sufficient detail.[4,6] At the same time, there is a great paucity of experimental data for the structure of such an SF in gases.

The SF were generated in a D_2 atmosphere or in the air ($P_1 = 0.5$–30 Torr) as a result of the separation of the plasma produced during focusing of the radiation from the "Kal'mar" laser device ($E_L \lesssim 250$ J, $\tau \approx 10^{-9}$ sec) on spherical targets [SiO_2, $(C_8H_8)_n$, ϕ 70–250 μm].[2] As a result of the use of high-speed optical photography methods,[7] two regions with a large electron density gradient ($\nabla n_e > 2\times 10^{19}$ cm^{-4}) were observed for the first time ≈ 30 nsec after irradiation of the target in deuterium at $p_1 \gtrsim 4$ Torr at the shock front. These regions are represented in Fig. 1a in the form of two dark, concentric rings (see also Fig. 1c). Moreover, such a structure was not observed in experiments performed in the air under similar conditions (Fig. 1b). By carefully analyzing the results of such experiments, we were able to establish that the observed "double" front of the SW is not the result of a visual representation of the "plasma target-plasma SF" contact boundary. In this case the inner dark ring (Fig. 1a) corresponds to the proper "mass" front of the SF and the outer dark ring corresponds to the D_2 ionization front which was formed as a result of the action of nonlinear, electronic thermal conductivity.[1)]

The source of thermal flux, which leads to formation of a deuterium ionization wave, generally can be both the target plasma and the SF plasma. Investigation of the dynamics of motion of the ionization and shock fronts, which was conducted by using Schlieren-image scanning on a photoelectron recorder (Fig. 1d), showed that the observed structure cannot be accounted for in terms of development of the thermal wave in a gas due to heating of the target. As seen in Fig. 2, the motion of an ionization front differs sharply from the propagation of a thermal wave from an instantaneous point source such as the target plasma (the case of electron thermal conductivity is described by the following equation[4]: $R_T = Ct^{2/19}$, where R_T is the radius of a thermal wave and C is a constant that depends on the liberated energy and on the gas density). A direct calculation of the motion of a thermal wave under the existing experimental conditions showed that its velocity is smaller than the initial velocity D_0 of the SW at $R_T > 0.15$ mm.

Thus, the observed structure, which forms the ionizing shock front, is not associated with the peculiarities of the method used to produce it. The experimental studies allowed us to determine that the width of the heated zone in deuterium satisfies the empirical equation:

$$\delta = \chi D^4 P_1^{-1}, \tag{1}$$

where $\chi = (7.0 \pm 1.5) \times 10^{-27}$ g·sec^2/cm^4. Both the structure in deuterium and the dependence (1) are in qualitative agreement with the theoretical representations of the strong SW front in a plasma.[4-6] In addition, the thickness of the heated layer obtained from the theoretical calculations always turns out to be slightly larger than the experimental value. Thus, for $D = 200$ km/sec at $p_1 = 16$ Torr, according to Ref. 4, $\delta = 1.75$ mm for the experimental value $\delta \approx 0.5$ mm. This discrepancy apparently is attributable to the fact that in the theoretical calculations the medium in which the SF is propagated was assumed to be ionized and the effect of ionization and dissociation of the gas on the structure of the front was disregarded. It seems that allowance for these processes should reduce the calculated width of the heated zone.

It should be noted that in order (compared to the discussed experimental conditions) gases and for other values of D and p_1 the dimensions of the heated zone may differ greatly from the observed dimensions, because of variation of the length of the mean free path of the particles. The last value, however, also determines the width of the "mass" front of the shock, so that the front of any ionizing shock must be a "double" structure similar to that described above. This fact apparently accounts for the small—smaller than spatial—resolution recording method—dimension of the heated zone in the air (Fig. 1b). In fact, at the characteristic values of $\rho_1 \sim 10^{-6}$ g/cm^3 and $T \sim 100$ eV, and for the performed experiments in a completely ionized deuterium, l, which is determined by the gas-kinetic ion dimensions, is ~ 0.01 mm. Thus, the heated zone in the air must also be an order of magnitude smaller than in D_2.

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[1)]The propagation of heat cannot be attributed to the radiant thermal conductivity because of the weak radiation power of the target-plasma[8] and of the shock-wave plasma[9] under the conditions of the experiments.

[2)]According to the estimates, the air in the shock wave was ionized not more than sixfold.

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