The dynamics of ionizing shock waves during the adiabatic motion of the gas

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The results of an experimental investigation of the laws governing the free (adiabatic) motion in deuterium of a spherical ionizing wave produced by an expanding laser plasma are presented. It is shown that the discrepancy between the free motion of shock waves that cause the complete ionization of the gas and the instantaneous-point-explosion model is not due to changes in the adiabatic exponent γ, and that the propagation of the shock waves occurs under conditions of constant $\gamma = 5/3$. This effect is related to the effect of the structure of the shock-wave front on the dynamics of the propagation of the wave. An analytical expression is found which describes the motion of symmetric ionizing shock waves to within 1%, and this has allowed an experimental determination of the adiabatic exponent to be carried out. A method for determining the energy of shock waves on the basis of the dynamics of their motion to within ~5% is developed.

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§1. INTRODUCTION

One of the interesting physical phenomena accompanying the expansion of a dense plasma heated by a high-power laser is the generation of strong ionizing shock waves in the residual gas surrounding the target, on which gas the expanding plasma acts like a piston.[1-4] It should be said that so far shock waves with such parameters (initial velocity ~10^7–10^8 cm/sec when the gas density ~10^{18}–10^{19} cm^{-3}) have been investigated largely theoretically,[5-8] and that these investigations have shown that the structure and the dynamics of the motion of such shock waves differ significantly from the parameters of the well-studied nonionizing (or slightly ionizing) shock waves. But the experimental data on intense shock waves are quite limited. This is due to the fact that the attainment under laboratory conditions of velocities ~10^7–10^8 cm/sec by the traditional methods (with the aid of, for example, shock tubes, explosives, etc.) turn out to be possible only in gases of relatively low density ($\lesssim 10^{15}$ cm^{-3}), which practically excludes the application of optical diagnostics methods possessing the necessary spatial and time resolutions.[9,10]

In view of this, the investigation of strong shock waves produced with the aid of a laser is of fundamental interest from the point of view of the elucidation of the general questions of the hydrodynamics of shock waves. On the other hand (and this will be demonstrated below) the understanding of the processes that occur during the formation and propagation of such shock waves allows us to develop procedures for the diagnostics of plasmas heated by high-power laser radiation.

In the present paper we report the results of an investigation of the "free"-propagation phase of a laser-generated ionizing shock wave, when the transfer of the energy of the piston (the expanding dense plasma) to the shock wave has completely ended, and the wave propagates without loss of inflow of energy.[1)]

§2. EXPERIMENTAL SETUP AND RESULTS

The experiments were performed on the high-power nine-channel "Kal'mar" laser facility. The experimental setup is described in detail in Refs. 1, 11, and 12. To investigate the dynamics of shock waves produced during the interaction of the laser radiation with spherical targets, we used the method of seven-frame high-speed streak photography.[11] The experiments were performed with spherical solid and shell glass targets with diameters ranging from 70 to 250 μm and at deuterium pressures ranging from 1.5 to 20 Torr. Under the action of the high-power light pulses the material of the target got heated to high temperatures (~0.1–1 keV), forming a plasma corona with a decreasing density profile, which began to expand into the surrounding space with velocity ~10^7–10^8 cm/sec. The expanding laser plasma, acting like a piston, set the gas surrounding the target in motion, and produced a shock wave.

Figure 1 shows a characteristic seven-frame streak photograph of a shock wave. The good spherical symmetry of the shock wave is noticeable. In all the experiments with the spherical glass targets the relative difference between the radii of the shock wave in different directions was not greater than several percent.[2)]

Figure 2 shows the R–t diagram of the shock-wave motion, obtained as a result of the processing of the photograph in Fig. 1. Usually, the free propagation of shock waves is described by the solution to the problem of instantaneous point explosion[13]:

$$R=(E_0/\alpha\rho_1)^{1/(\nu+2)}t^{2/(\nu+2)}, \tag{1}$$

where R is the radius of the shock wave, E_0 is the total shock-wave energy, ρ_1 is the initial gas density,[3)] t is the time, and $\nu=1$, 2, and 3 are respectively for plane, cylindrical, and spherical symmetry. The quantity α is a functional, being dependent on ν, the adiabatic exponent γ, and the form of the distribution functions behind the shock-wave front of the dimensionless density $\tilde{\rho}=\rho/\rho_2$, pressure $\tilde{p}=p/p_2$, and velocity $\tilde{v}=v/v_2$ of the ordered motion of the gas:

$$\alpha=\frac{8\sigma_\nu}{(\nu+2)^2(\gamma^2-1)}\int_0^1(\tilde{p}+\tilde{\rho}\tilde{v}^2)\tilde{r}^{\nu-1}d\tilde{r}, \tag{2}$$

$$\sigma_\nu=2(\nu-1)\pi+(\nu-2)(\nu-3),$$

where $\tilde{r}=r/R$ is the dimensionless radius.

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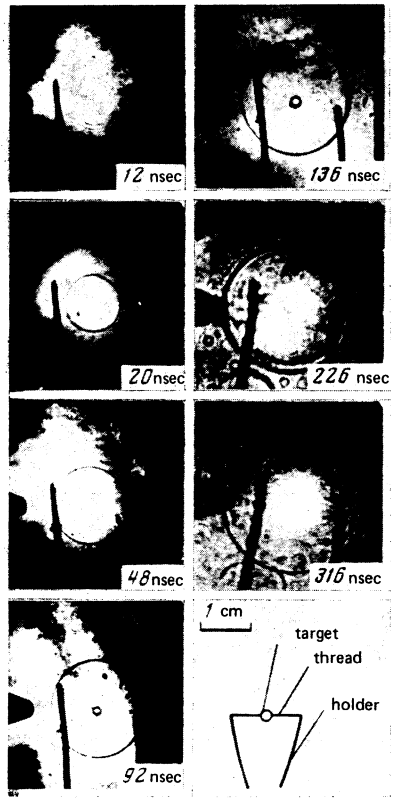

FIG. 1. Seven-frame streak photograph of a shock wave in deuterium. The pressure $p_1 = 8$ Torr. The moments of exposition, reckoned from the beginning of the heating of the target, are indicated on the frames.

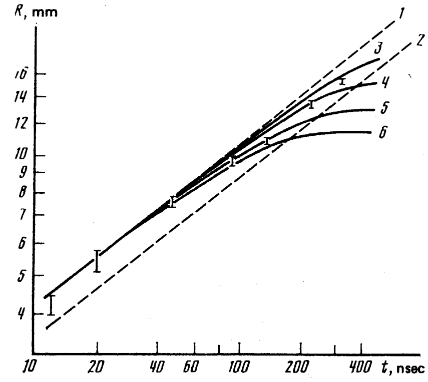

FIG. 2. $R-t$ diagram, corresponding to Fig. 1, of the shock-wave motion. The dashed lines represent the self-similar solution (1) to the point-explosion problem: 1) $E_0/\alpha = 28.7$ J; 2) $E_0/\alpha = 10.3$ J. The continuous curves depict the dependence (8) for an ionizing shock wave ($E_0/\alpha = 28.7$ J): 3) $\gamma = 1.2$, $E_0 = 49.6$ J; 4) $\gamma = 1.4$, $E_0 = 24.5$ J; 5) $\gamma = 1.67$, $E_0 = 14$ J; 6) $\gamma = 2.0$, $E_0 = 9$ J. The error for the fourth point (at 92 nsec) was erroneously increased by a factor of two in the figure.

But Eq. (1) describes only very approximately the motion of ionizing shock waves, since at least two important characteristics of their propagation are neglected in the derivation of (1). First, the energy of such a shock wave is expended during the motion not only on the heating and the kinetic motion of the gas, but also on the dissociation and ionization of the gas molecules and atoms, it being possible for the fraction of the latter in the energy balance to attain appreciable values (up to ~50%). Secondly, it is well known[8] that in ionizing shock waves the adiabatic exponent can be strongly dependent on the temperature behind the front and, consequently, on the wave velocity D. Since the latter quantity continuously decreases during the free motion, this may cause corresponding changes in γ, a possibility which is also neglected in the derivation of (1).

In Fig. 2 the dashed straight lines correspond to the solution to Eq. (1) for different values of the parameter E_0/α. The free divergence of the shock wave, the dynamics of which differed markedly from the motion in the initial phase, in which the transfer of the energy of the target plasma to the shock wave occurred, began ~15–20 nsec after the irradiation of the target. In this case, according to estimates of the gas temperature behind the shock front, the ionizing-shock-wave phase in this experiment continued for up to ~150 nsec after the irradiation of the target. According to a previous investigation,[11] it is precisely in this phase that the position of the front can be most accurately determined (to within ≈1%) by means of active optical sounding. Furthermore, excluded here are the systematic errors that can arise during the detection of nonionizing shock waves as a result of, for example, the visual representation of the gas-ionization front, which is located in this case behind the shock front. It can be seen from the figure that only a small section of the $R-t$ diagram of the shock wave (the section in the interval $20 \leq t \leq 35$ nsec) approximately corresponds to the theoretical dependence (1). At the same time, the error in the measurement of the shock-wave radius on this section is relatively large (up to ~20%) because of the large width of the leading edge of the shock wave.[11] Significant deviations of the shock-wave motion from the dependence (1) are observed during the subsequent divergence of the wave. The motion of a nonionizing shock wave (the two points in the $t > 200$ nsec region in Fig. 2) approximately corresponds to Eq. (1), for lower E_0/α values, however. This shows that the quantity α varies either continuously during the motion of the shock wave, or during the transition of the shock wave into the nonionizing state. It is convenient to estimate the degree of approximation with which the solution (1) describes the motion of an ionizing shock wave from the accuracy with which Eq. (1) allows us to determine the initial energy E_0 of the explosion.

Let us note that the determination of this quantity is of great practical importance (see §4). It can be seen from Fig. 2 that the experimental points lie on straight lines corresponding to the dependence (1), and differing in their E_0/α values by roughly a factor of 1.5. At the same time, to find the shock-wave energy E_0, we must determine the quantity α, which depends on the adiabatic exponent. Since there are no high-speed methods of determining γ in a shock wave, we can only assume, in accordance with the theoretical ideas, that $\frac{5}{3} \leq \gamma \leq 1.2$ (Ref. 8). The quantity α then changes by a factor of 3.5, and the determination of E_0 proves to be possible to within ~500%.

§3. THE DYNAMICS OF THE SHOCK-WAVE MOTION UNDER CONDITIONS OF IONIZATION AND DISSOCIATION

Let us consider the equation of motion of freely propagating ionizing shock waves, which is obtainable from an analysis of the energy balance in the shock waves:

$$E_k+E_t+E_i+E_r=E_0, \tag{3}$$

where E_k and E_t are respectively the kinetic and thermal energies of the shock-wave particles, E_i is the ionization and dissociation potential of the atoms and molecules of the gas, and E_r is the radiation energy emitted by the shock wave. Estimates show that, for an initial shock-wave temperature $T_2<1$ keV in deuterium, E_r is negligibly small. The other quantities entering into (3) can (following Ref. 14) be represented in the form

$$E_k=\sigma_\nu\int_0^R\frac{\rho v^2}{2}r^{\nu-1}dr,\quad E_t=\sigma_\nu\int_0^R\frac{pr^{\nu-1}}{\gamma-1}dr,\quad E_i=\sigma_\nu\frac{\rho_1\varepsilon r^\nu}{\nu}, \tag{4}$$

where ε is the specific ionization and dissociation energy per unit mass of the gas. Expressing the integrals entering into (4) in terms of the dimensionless quantities $\tilde{\rho}$, $\tilde{p}$, $\tilde{v}$, and $\tilde{r}$, and using the equations relating the parameters of the gas in a strong shock wave,[8] we can write

$$E_k=A_\nu\dot{R}^2R^\nu,\quad E_t=B_\nu\dot{R}^2R^\nu,\quad E_i=C_\nu R^\nu, \tag{5}$$

where

$$A_\nu=\frac{2\sigma_\nu\rho_1}{\gamma^2-1}J_1,\quad B_\nu=\frac{2\sigma_\nu\rho_1}{\gamma^2-1}J_2,\quad C_\nu=\frac{\sigma_\nu\rho_1\varepsilon}{\nu},$$

$$J_1=\int_0^1\tilde{\rho}\tilde{v}^2\tilde{r}^{\nu-1}d\tilde{r},\quad J_2=\int_0^1\tilde{p}\tilde{r}^{\nu-1}d\tilde{r}.$$

The sum of the coefficients A_ν and B_ν then determines the quantity α [see (2)]:

$$\alpha=\frac{8\sigma_\nu(J_1+J_2)}{(\nu+2)^2(\gamma^2-1)}=\frac{4(A_\nu+B_\nu)}{(\nu+2)^2\rho_1}. \tag{6}$$

Using (5) and (6), we can write Eq. (3) as

$$\dot{R}^2R^\nu/K+R^\nu=R_k^\nu,$$

$$K=\frac{C_\nu}{A_\nu+B_\nu}=\frac{4\sigma_\nu\varepsilon}{\alpha\nu(\nu+2)^2},\quad R_k=\left[\frac{4E_0}{(\nu+2)^2\alpha K\rho_1}\right]^{1/\nu}. \tag{7}$$

Equation (7) describes the motion of an ionizing shock wave, and has been derived without the use of simplifying assumptions (with the exception of the condition $E_r \ll E_0$). This equation would be easy to solve analytically if the coefficients R_r and K entering into it were constants. It can be seen that $R_r=\text{const}$ in the case in which $\varepsilon=\text{const}$, i.e., in a shock wave that causes the total ionization of the gas, a condition which is fulfilled, in particular, for an ionizing shock wave in deuterium. At the same time, the coefficient $K(\alpha)$ should be a function of the time, since the problem under consideration is not self-similar (because of the introduction, in comparison with the instantaneous-point-explosion problem, of the additional dimensional parameter ε), and the distributions $\tilde{v}(\tilde{r})$, $\tilde{p}(\tilde{r})$, and $\tilde{\rho}(\tilde{r})$, which determine the quantity α, cannot be steady-state distributions.

But there are physical reasons that allow us to expect the dependence $\alpha(t)$ to be weak. Earlier,[3] we demonstrated experimentally that there exists in front of the ionic (mass) front of an ionizing shock wave in deuterium a gas layer that is fully ionized on account of the electronic heat conduction, whose source is the plasma of the shock wave itself, the width δ_t of this layer being roughly two orders of magnitude greater than the width δ_i of the shock compression. Although this effect was directly observed only when $D \gtrsim 10^7$ cm/sec, the relation $\delta_t \gg \delta_i$ should be preserved over the entire phase of existence of the ionizing shock wave, since

$$\delta_t \propto (m_i/m_e)^{1/2}l_0,$$

while $\delta_i \propto l_0$ (l_0 is the mean free path of the particles of the shock-wave plasma).[6] For such a front structure, the dissipation processes occur in the shock compression in the same manner as in a shock wave propagating in a fully ionized plasma. Therefore, it may be expected that in an ionizing shock wave $\gamma=\frac{5}{3}$, while v_2/D, ρ_2/ρ_1, $p_2/\rho_1D^2=\text{const}$. As has already been noted, α depends quite strongly on the adiabatic exponent; therefore, the constancy of γ substantially limits the possible range of variation of α. Moreover, analysis of the expression (2) shows that the value of α is slightly sensitive to a change in the form of the functions[4)] $\tilde{\rho}(\tilde{r})$, $\tilde{v}(\tilde{r})$ and $\tilde{p}(\tilde{r})$. This gives rise to a situation in which the quantity α may change insignificantly even when the density, velocity, and pressure distributions behind the front undergo substantial transformations as a result of the shock-wave motion (during which v_2/D, ρ_2/ρ_1, $p_2/\rho_1D^2=\text{const}$). Undoubtedly, these assumptions require further verification. To do this, let us find the solution to Eq. (7) under the assumption that $\alpha=\text{const}$. It has the form

$$\tau=F_\nu(X)/F_\nu(1);$$

$$\tau=\frac{t}{t_k},\quad X=\frac{R}{R_k},\quad F_\nu(X)=\int_0^X(y^{-\nu}-1)^{-1/2}dy, \tag{8}$$

$$t_k=\frac{R_k}{K^{1/2}}F_\nu(1).$$

To find the limits of the integration here, we used the obvious condition according to which the solution (8) should tend to (1) as $t\to 0$ ($E_i\to 0$). For $\nu=1,2$ the functions $F_\nu(X)$ can be expressed in terms of elementary functions:

$$F_1(X)=\arcsin X^{1/2}-[(X-1)X]^{1/2},\quad F_2(X)=1-(1-X^2)^{1/2}. \tag{9}$$

For $\nu=3$ the function $F_3(X)$ can be expressed in a complicated manner in terms of a linear combination of elementary functions and normal Legendre elliptic integrals of the first, second, and third kinds. It is convenient for practical applications to tabulate $F_\nu(X)$ with the aid of a computer. The results of the corresponding computations are shown in Fig. 3 in the form of a plot of $F_\nu(X)$. It is not difficult to verify in accordance with (4) that t_k and R_k are the coordinates of a point of the $R-t$ diagram in the case in which the entire shock-wave energy is converted into E_i (in this case $\dot{R}=0$).[5)]

The quantity K also has a clear physical meaning: it determines the difference between the shock-wave velocity when allowance is made for the "loss" due to ionization and the velocity when this "loss" is neglected (i.e.,

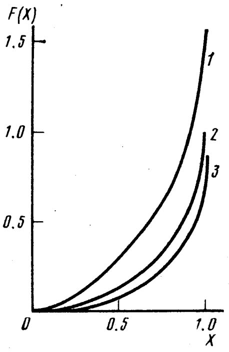

FIG. 3. Plot of the functions $F_\nu(X)$: 1) $\nu=1$; 2) $\nu=2$; 3) $\nu=3$.

the velocity in the instantaneous-point-explosion problem):

$$\dot{R}^2=D_c^2-K;\quad D_c\equiv[4E_0/(\nu+2)^2\alpha\rho_1R^\nu]^{1/2}, \tag{10}$$

where D_c is the velocity of a shock wave with radius given by (1). The relation between the potential and kinetic energies of the particles in the shock wave are, according to (5) and (8), determined by the shock-wave velocity and the quantity K:

$$\frac{E_i}{E_k+E_t}=\frac{K}{\dot{R}^2}. \tag{11}$$

An interesting characteristic of the solution obtained is the fact that the dimensional quantities characterizing the shock-wave propagation conditions—the energy E_0, the initial density, the ionization and dissociation potentials of the gas—enter into it only through the values of t_k and R_k. And the form of the function $F_\nu(X)$ does not depend on the specific values of these parameters. A consequence of this is the following single-valued relation between the dimensionless radius X and the shock-wave velocity:

$$X=\left(\frac{K}{K+\dot{R}^2}\right)^{1/\nu}. \tag{12}$$

Therefore, the region of applicability of the solution (8) is, for a given gas, determined irrespective of the quantities E_0 and ρ_1 by a definite range of variation of $X<X^*$, where X^* corresponds to the temperature behind the shock-wave front at which appreciable recombination of the ions begins. Since it is complicated to establish with sufficient accuracy within the framework of the existing ideas the relation $T_2(\dot{R})$ for the case of free shock-wave expansion, the value of X^* was determined experimentally, and was found to be ≈ 0.87 for deuterium.

Of extremely great importance for practical application are the various functional dependences of the solution (8) on E_0 and α. Indeed, according to (8),

$$t\propto\alpha^{-1/2}E_0^{1/\nu}F_\nu(X(E_0)).$$

Thus, the assumption that $\alpha=\text{const}$ turns out to be experimentally verifiable: from the experimental $R-t$ diagram we can independently find the quantities E_0 and α. In Fig. 2 the continuous curves depict the dependence (8) for different values of E_0 and $\alpha(\gamma)$. It can be seen that the experimental points coincide well with the curve described by (8) with $\alpha=0.487$ ($\gamma=\frac{5}{3}$, $\nu=3$) and $E_0\approx 14$ J. Similar results were obtained in all the experiments performed in the parameter regions $1.5\leq p_1\leq 20$ Torr and $0.5\leq E_0\leq 25$ J. In all these cases the quantity α remained constant to within the experimental error, and its value (=0.487) showed that the adiabatic exponent $\gamma=\frac{5}{3}$ in an ionizing shock wave in deuterium, and the form of the distribution functions $\bar{\rho}(\bar{r}), \bar{v}(\bar{r})$, and $\bar{p}(\bar{r})$ remained close to the form of the corresponding functions obtained in the solution of the instantaneous-point-explosion problem.[14] These results confirm the correctness of the assumptions made above.

§4. A METHOD FOR DETERMINING THE ENERGY OF A SHOCK WAVE

The investigation of the dynamics of the free motion of shock waves is of great applicative importance, in particular, in connection with dense-nonstationary-plasma diagnostics, since the correct interpretation of the laws governing the propagation of shock waves produced under the action of an expanding plasma allows us to determine the energy $E_{\rm pl}$ of the latter. Especially promising is the application of this method to laser-plasma diagnostics in the spherical irradiation geometry. The point is that the majority of existing methods of determining $E_{\rm pl}$ under conditions of spherical-target irradiation have a fundamental shortcoming: a small observation solid angle.[17-20] Under conditions of anisotropic refraction of the heating radiation and dispersion of the target material,[21-23] the use of such methods can lead to indefinitely large measurement errors. The method of determining $E_{\rm pl}$ on the basis of shock-wave dynamics is free from this disadvantage. But the error in the determination of the shock-wave energy[6)] through comparison with the instantaneous-point-explosion model[4,24] turns out to be very large (~500%; see §2). The introduction of corrections for ionization and dissociation by adding E_i (easily determined from the experimental $R-t$ diagram of the shock wave) to the E_0 value obtained with the aid of (1) also does not solve the problem. The fundamental error in this case is that, for E_i comparable to E_k+E_t, the ionizing-shock-wave velocity, which, in the final analysis, determines the thermal and kinetic energies of the particles in the shock wave, differs significantly from the value ascribed [by the use of the dependence (1)] to it [see the expression (10)].

In the preceding section we showed that the dependence (8) describes the free motion of symmetric ionizing shock waves to within the experimental error (which is better than ~1%). The use of this dependence allows us to determine from the experimental $R-t$ diagram the energy E_0 of the shock wave with a significantly higher degree of accuracy. But in the case of spherical shock waves these computations turn out to be nontrivial because of the fact that the solution (8) contains nonelementary functions. To determine the quantity E_0 analytically from the experimental points (R_j, t_j); it is convenient to use tables of the functions $\phi_3(X)\equiv F_3(X)/X$, which are easy to construct with the aid of a computer. As has already been noted, the form of these functions does not depend on the experimental conditions. The following algorithm for determining E_0 can be proposed:

TABLE I.

Frame no.	t, nsec	R, mm	X	E_0, J
1	12	2.9–4.05	0.315–0.473	1.5–7.6
2	20.3	5.0–5.6	0.406–0.469	7.4–13.7
3	47.8	7.2–7.5	0.617–0.630	9.4–11.3
4	92.1	9.2–9.4	0.776–0.781	10.1–11.0
5	136.3	10.45–10.8	0.867–0.875	10.3–11.8
6	226	12.1–12.9	0.968–0.981	11.7–14.9
7	315.8	14.6–15.0	0.993–0.995	19.9–21.1

1) the quantity $\phi_3(X_j)=K^{1/2}t_j/R_j$ is computed from the experimental points; 2) the quantity X_j corresponding to the $\phi_3(X_j)$ value found is determined from the table; 3) the shock-wave energy is found from the formula $E_0=C_3(R_j/X_j)^3$, which follows directly from (5), (11), and (12).

Table I illustrates the computation of the shock-wave energy for one of the experiments. The indicated E_0 spread corresponds to the experimental error made in the measurement of R. It can be seen from the table that, within the limits of the experimental error, the E_0 values for $t\lesssim 150$ nsec (i.e., in the phase of existence of the ionizing shock wave) are in good agreement with each other, with the exception of the first frame. This is explained by the fact that the transfer of the energy of the expanding target plasma to the shock wave was continuing at that instant, and the phase of free motion had still not begun.

The direct computation of the experimental error for E_0 in accordance with (8) is complicated, and, to determine it, it is more convenient to compute the quantity E_0 for the two values $R_j+\Delta R_j$ and $R_j-\Delta R_j$ at each experimental point, as shown in Table I. For the experiment reported here $E_0=10.5\pm 0.5$ J, which corresponds to $a\sim 5\%$ error. The magnitude of the latter is determined by the error ΔR made in the measurement of the shock-wave radius, an error which, according to Erokhin *et al.*,[11] is connected with the dimension and structure of the shock-wave front. It has been experimentally established that the quantity ΔR has its minimum value at $X\approx 0.75$ ($\dot{R}\approx 3.76\cdot 10^6$ cm/sec). Since the shock-wave velocity completely determines the structure of the wave front, this assertion should be true for other E_0 scales, which allows us to choose the optimum moment t_m for the recording of the shock wave by substituting the values $X=0.75$ into the expression (8). Thus, for an explosion energy $E_0\sim 10^3$ J, which will be characteristic of the next-generation high-power laser facilities of the "Del'fin"[25] and "SHIVA"[26] types, we have $t_m\approx 260$ nsec in deuterium at $p_1=20$ Torr.

It should be noted that the value of E_0 obtained by the proposed method may contain, besides the error due to the inaccuracy in the measurement of R, a systematic error connected with the use of the value[7)] $\alpha=0.487$ in the calculations. Strictly speaking, the experimental data obtained allow us to assert that in the case of the motion of an ionizing shock wave $\alpha=0.48\pm 0.10$ with a relative error of $\Delta\alpha/\alpha\approx 20.8\%$. It can be shown that the systematic error made in the determination of E_0 is then equal to

$$\left(\frac{\Delta E_0}{E_0}\right)_s=\frac{3(1-X^3)^{1/2}F_3(X)}{2[(1-X^3)^{1/2}F_3(X)+X^{3/2}]}\frac{\Delta\alpha}{\alpha}.$$

For $X=0.75$, which corresponds to the minimum value of the error ΔR, the systematic error $(\Delta E_0/E_0)_s\approx 8\%$.

§5. CONCLUSION

The experimental investigations showed that the free motion of a shock wave that causes the complete ionization of the gas occurs under conditions of a constant adiabatic exponent $\gamma=\frac{5}{3}$, and that the form of the distributions $\tilde{\rho}(\tilde{r})$, $\tilde{v}(\tilde{r})$, and $\tilde{p}(\tilde{r})$ is close to the form of the corresponding functions obtained in the solution of the instantaneous-point-explosion problem.[13] In this case the deviation of the motion of the ionizing shock wave from the dependence $R\sim t^{2/5}$ is due only to the energy "losses" resulting from the ionization and dissociation of the gas. It can be asserted that these physical characteristics are peculiar (at least) to shock waves that cause the complete ionization of the gas, in particular, to ionizing shock waves in deuterium and hydrogen, and are due largely to the existence of a heated layer in front of the shock compression.[3] Thus, these characteristics are not connected with the method used to produce the shock waves in the investigation, but are a fundamental property of the shock waves themselves.

The value of the adiabatic exponent and the parameters of the shock compression of ionizing shock waves that cause the partial ionization of the gas should depend on the form of the spatial distribution in the shock-wave front of the energy losses due to ionization. In particular, if the major portion of these losses occurs at points far in front of the shock compression (inside the heated layer), then the properties of such shock waves should be similar to those described in this paper. But this question requires the performance of additional investigations.

In conclusion, the authors express their gratitude to I.V. Nemchinov and V.B. Rozanov for valuable comments.

1)Sometimes this phase is called the "adiabatic" expansion of the shock wave.

2)The double ring corresponding to the shock-wave front, which can be seen in the first frame (12 nsec), is due to the visual representation of the ionization front in front of the "mass" (ionic) front of the shock wave. As shown in Ref. 3, this phenomenon is caused by the effect of the nonlinear electronic thermal conductivity. The influence of this effect on the dynamics of the shock-wave expansion will be discussed below.

3)Here and below the subscripts 1 and 2 respectively denote the quantities pertaining to the regions before and after the shock-wave front.

4)Thus, Chernyĭ[15] has shown that the transformation of the self-similar distributions $\tilde{\rho}(\tilde{r})$, $\tilde{v}(\tilde{r})$, and $\tilde{p}(\tilde{r})$ even into step-like distributions does not lead to a significant change in α.

5)It is evident that the point of the $R-t$ diagram with the coordinates $R=R_k$, $t=t_k$ is not in actual fact realized, since the solution (8) is applicable only to ionizing shock waves.

6)Notice that the quantities E_{pl} and E_0 can differ from each other as a result of the incomplete transfer of the plasma energy to the shock wave. This question will not be discussed within the framework of the present work.

7)This value may be inexact (within the limits of the experimental error made in the determination of α) because of the difference between the form, assumed here, of the distributions $\tilde{\rho}(\tilde{r})$, $\tilde{v}(\tilde{r})$, and $\tilde{p}(\tilde{r})$, which were taken from the solution to the instantaneous-point-explosion problem,[14] and the form of the real distributions, a difference which is due to the transformation of these functions during the motion of the shock wave, the effect of the heat conduction inside the shock wave, and a number of other causes.

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