17. I. A. Kirillov, B. V. Potapkin, et al., "On the influence of the original spatially inhomogeneous temperature perturbations on the dynamics of vibrational relaxation," Zh. Prikl. Mekh. Tekh. Fiz., No. 6, (1984).
18. P. A. Sergeev and D. I. Slovetskii, "The determination of the gas and electron temperatures using the form of the distribution of populations of the vibrational levels of the molecules," Khim. Vys. Energ., 18, No. 1, (1984).

# PARTICLE CHARGING IN "HOT" AEROSOLS

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Electrification of highly conductive alpha- and beta-active particles in dispersed media is studied. In order to do so, a single ideally conductive radioactive particle of spherical form, located within a nonmoving gas containing ions of both signs, is studied. It is assumed that the ion concentration and particle dimensions are so small that the intrinsic electric field of the ions may be neglected. In contrast to [3, 4], this study considers the case in which the contribution of external readiation sources (including the contribution of radiation of other particles in the aerosol) to gas ionization is the major one. The results of solution of the analogous problem for nonradioactive particles were presented in [5, 6]. We consider the problem of determining equilibrium concentrations of ions and radioactive particle charge with consideration of ion absorption by the particles. Relationships are obtained and studied, which describe the equilibrium state of a monodispersed radioactive medium, analogous to the Sach equations for ionized gases or the equations of the law of acting masses for chemically reacting gas masses [1].

1. In radioactive aerosols the charges of particles can change due to capture of gas ions and because of radiation of alpha- or beta-particles. Propagation of radiation through the gas leads to its ionization. In connection with this, the charge of particles and concentration of ions depend significantly on the concentration of particles and their individual activity, which for the most dangerous ("hot") particles can reach values of the order of hundreds of Bq (decays/sec) and more [7]. In order to study this phenomenon in the case of a low volume concentration of the dispersed phase we will first consider electrification of a single spherical particle in a gas which simultaneously contains ions of both signs. The equation describing particle electrification has the form

$$\frac{dQ}{dt} = Y + e(i_+ - i_-), \tag{1.1}$$

where Q is the particle charge; $i_\pm$ is the flux of positive and negative ions toward the particle; e is the charge of a proton; Y is the rate of change of charge due to radioactive radiation. For definiteness, we will assume below that $Y \geq 0$, which does not affect the generality of the results obtained.

The quantity Y is related to the particle activity C by the equation Y = emC (where m is the mean number of elementary charges lost by the particle in a single decay). We assume that the particle diameter is so small that radiation braking within the particle can be neglected, so that the relationship $m \ll \eta$ is satisfied (where $\eta$ is the mean number of ion pairs formed by radiation in the gas in a single decay).

In the case of electronic beta-decay m = 1, while for alpha-decay due to secondary electron emission the quantity m is positive and may reach values of the order of 10-20 [8].

We will consider the state of the electric field perturbed by a particle and the distribution of ion concentrations. We assume that the particle is ideally conductive and that all ions reaching the surface of the particle instantly transfer their charge to the particle.

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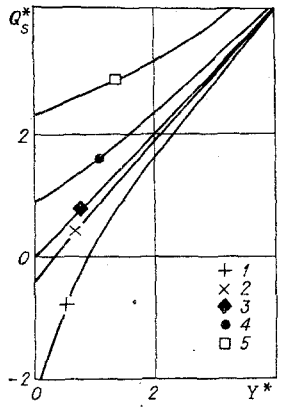

Fig. 1

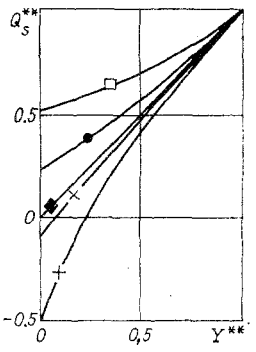

Fig. 2

We assume further that the conditions $E^* \gg 4\pi a e n_\pm$, $C\lambda/(4\pi D_\pm n_\pm) \ll 1$, where $E^*$ is the characteristic electric field intensity, $\lambda$ is the linear ionization density, and $n_\pm$ and $D_\pm$ are the unperturbed concentrations and ion diffusion coefficients. With these assumptions the distortion of the electric field in the vicinity of the particle produced by ionic space charge is small, and the distribution of ions and their fluxes per particle is independent of volume ionization and recombination.

2. We will consider the case in which the intensity E of the applied electric field and the particle size are sufficiently small:

$$\frac{aeE}{kT} \ll 1. \tag{2.1}$$

Here k is Boltzmann's constant, T is absolute temperature. Upon satisfaction of Eq. (2.1) and the assumptions made above, we have for the ion fluxes to the particle, we have in place of the expression of [5]

$$i_\pm = \pm 4\pi a D_\pm n_\pm \frac{Qe}{akT}\left[\exp\left(\pm\frac{Qe}{akT}\right) - 1\right]^{-1}. \tag{2.2}$$

The ionic diffusion coefficients are related to the ionic mobilities $b_\pm$ by the Einstein expressions $b_\pm = \pm eD_\pm/(kT)$. To study Eq. (1.1) in the case under consideration it will be convenient to transform to dimensionless variables

$$Q^* = \frac{Qe}{akT}, \quad Y^* = \frac{Y}{4\pi a e n_- D_-}, \quad \tau = 4\pi e n_- |b_-| t, \quad \varkappa = \frac{b_+ n_+}{|b_-| n_-}. \tag{2.3}$$

Equation (1.1) then takes the form

$$\frac{dQ^*}{d\tau} = Y^* + \varkappa Q^* (\exp Q^* - 1)^{-1} + Q^* [\exp(-Q^*) - 1]^{-1}. \tag{2.4}$$

The steady-state charge $Q_S$ can be found from the functional equation

$$Y^* = Q_s^* (\exp Q_s^* - \varkappa)/(\exp Q_s^* - 1), \quad Q_s^* = \frac{eQ_s}{akT}. \tag{2.5}$$

The functions $Q_S^*(Y^*)$ are shown in Fig. 1 for $\varkappa$ = 0.1; 0.7; 1.0; 2.5; 10 (points 1-5).

At $\varkappa$ = 1 we find from Eq. (2.4) that

$$Q = Q_s(1 + C_0 e^{-\tau}), \quad Q_s = \frac{Y}{4\pi e n_- |b_-|} \tag{2.6}$$

(where $C_0$ is a constant determinable from the initial conditions).

It follows from Eqs. (2.4), (2.5) that if $\varkappa \neq 1$, then in the limiting case $Y^* \gg |\varkappa - 1|$, where the particle activity is sufficiently high, electrification at large values of the dimensionless time $\tau$ and the equilibrium charge values are also described by Eq. (2.6). In this case the sign of the equilibrium charge is always positive, while the value of the charge depends only on the particle activity and the quantity $\sigma_- = e|b_-|n_-$, which is the contribution of negative ions to the gas conductivity $e(b_+ n_+ + |b_-|n_-)$.

If the condition $Y^* \ll \varkappa \ln\varkappa/(\varkappa - 1)$ is satisfied, the equilibrium value of particle charge can be found from an asymptotic expression stemming from Eq. (2.5):

$$Q_s^* = \ln \varkappa + \frac{\varkappa - 1}{\varkappa \ln \varkappa} Y^* + o\left(\frac{\varkappa - 1}{\varkappa \ln \varkappa} Y^*\right). \tag{2.7}$$

The equilibrium charge value $Q_S = (akT/e)Q_S^*$ then depends significantly on particle radius. As follows from Eq. (2.7), the sign of the charge will be negative for sufficiently small values of the parameter $\varkappa = b_+ n_+ / |b_-| n_-$.

As an example, we will consider a beta-active particle (Y = Ce) with radius $a = 10^{-6}$ m, activity C = 100 Bq in dry atmospheric air under normal conditions ($D_- = 4.3 \cdot 10^{-6}$ m$^2$/sec, $D_+ = 2.8 \cdot 10^{-6}$ m$^2$/sec [9]). At a negative ion concentration value $n_-$ of $10^{11}$ m$^{-3}$, the parameter $Y^* = 18.5$. If the quantities $n_+$ and $n_-$ are of the same order the steady-state particle charge is defined by Eq. (2.6) and equal to $Q_S = 5.2 \cdot 10^{-17}$ C.

3. We will consider the case in which the particle radius and applied electric field intensity E are sufficiently large that the condition

$$eaE/kT \gg 1. \tag{3.1}$$

is satisfied. With the assumptions made in Sec. 1 and satisfaction of Eq. (3.1) the ion fluxes toward a particle are given by the expressions of [6]

$$i_\pm = \begin{cases} 0, & Q \gtrless \pm 3a^2E, \\ \pm \dfrac{\pi b_\pm n_\pm}{3a^2E} (Q \mp 3a^2E)^2, & |Q| \leqslant 3a^2E, \\ -4\pi b_\pm n_\pm Q, & Q \lesseqgtr \mp 3a^2E. \end{cases} \tag{3.2}$$

Equation (1.1), which describes particle electrification, can be integrated analytically. At the initial moment t = 0 let us assume the particle to be not electrified.

We will introduce the dimensionless quantities

$$Q^{**} = \frac{Q}{3a^2E}, \quad Q_s^{**} = \frac{Q_s}{3a^2E}, \quad Y^{**} = \frac{Y}{12\pi a^2 e n_- |b_-|}. \tag{3.3}$$

At $\varkappa = 1$ and any values of $Y^{**}$ the dependence of particle charge on dimensionless time $\tau = 4\pi e n_- |b_-| t$ is described by Eq. (2.6) with the value of the constant $C_0 = -1$. At $\varkappa \neq 1$ the solution has the form

$$Q^{**} = \frac{\varkappa + 1}{\varkappa - 1}\left[1 - \frac{4}{(\varkappa + 1)\tau + 4}\right], \quad \Lambda \equiv \varkappa + (1 - \varkappa) Y^{**} = 0; \tag{3.4}$$

$$Q^{**} = \frac{1}{\varkappa - 1}\left[\varkappa + 1 - 2\xi \frac{\varkappa + 1 + \operatorname{sgn} \Lambda 2\xi f(\xi\tau/2)}{2\xi + (\varkappa + 1) f(\xi\tau/2)}\right],$$

$$\xi = |\Lambda|^{1/2}, \quad f(x) = \begin{cases} \operatorname{th} x, & \Lambda > 0, \\ \operatorname{tg} x, & \Lambda < 0. \end{cases} \tag{3.5}$$

When $Y^{**} \leq 1$, Eqs. (3.4), (3.5) describe particle electrification for $0 \leq \tau < \infty$. The equilibrium charge value is given by the expression

$$Q_s^{**} = (\varkappa + 1 - 2\xi)/(\varkappa - 1). \tag{3.6}$$

If $Y^{**} > 1$, then Eqs. (3.4), (3.5) are valid only for a finite time interval ($0 \leq \tau \leq \tau_0$), while the value of $\tau_0$ can be found from the condition $Q^{**}(\tau_0) = 1$. For $\tau_0 < \tau < \infty$ the particle charge is described by Eq. (2.6) with the constant $C_0 = \exp \tau_0 (1 - Y^{**})/Y^{**}$.

Curves of the functions $Q_S^{**}(Y^{**})$ for various $\varkappa = n_+ b_+ / (n_- |b_-|)$ are shown in Fig. 2 (notation as in Fig. 1). From the definitions of Eq. (3.3), Eq. (3.6), and Fig. 2 it follows that for a relatively low particle activity ($Y^{**} < 1$) the sign of the equilibrium charge may be negative for a sufficiently small value of the parameter $\varkappa$, while the equilibrium charge value at $\varkappa \neq 1$ depends significantly on particle radius and the applied electric field.

If the particle activity is sufficiently high ($Y^{**} \geq 1$) or the condition $\varkappa = 1$, the equilibrium charge value $Q_S$ is defined by Eq. (2.6), while the charge value depends only on the particle activity and $\sigma_- = e|b_-|n_-$, the sign of the charge being always positive.

4. It was shown in Secs. 2 and 3 that the value of the equilibrium charge taken on by a particle depends significantly on the unperturbed ion concentration and the external electric field E. For a small volume particle concentration in the aerosol these quantities coincide

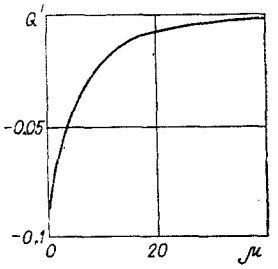

Fig. 3

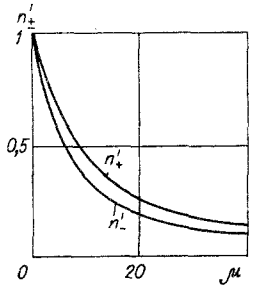

Fig. 4

with the averages appearing in the following macroscopic equations describing motion of the medium:

$$\frac{\partial n_\pm}{\partial t} + \operatorname{div} \mathbf{I}_\pm = \omega_\pm - \alpha n_+ n_- - n_p i_\pm,$$
$$\mathbf{I}_\pm = -D_\pm \nabla n_\pm + n_\pm (\mathbf{u} + b_\pm \mathbf{E}),$$
$$\operatorname{div} \mathbf{E} = 4\pi [e(n_+ - n_-) + Q n_p],$$
$$\frac{dQ}{dt} = Y + e(i_+ - i_-). \tag{4.1}$$

Here $n_p$ is the concentration of dispersed particles, which are considered identical and in satisfaction of the conditions of Sec. 1, $\mathbf{u}$ is the gas velocity, $\omega_\pm$ are the local rates of formation of positive and negative ions, $\alpha$ is the recombination coefficient. We will neglect motion of the dispersed particles relative to the gas.

Each of the alpha- or beta-particles radiated upon radioactive decay forms a large (on the average $10^3$-$10^5$) number of ion pairs in the gas, so that we will assume below that $\omega_+ = \omega_- = \omega$. For known functions $\omega$, $\mathbf{u}$, $i_\pm$ the solution of system (4.1) can be determined by specifying initial and boundary conditions.

We will consider the equilibrium state where all parameters of the dispersed medium are constant. We introduce the dimensionless quantities

$$n'_\pm = \frac{n_\pm}{n_0}, \quad n_0 = \sqrt{\frac{\omega}{\alpha}}, \quad \mu = \frac{n_p i_0}{\omega}, \quad i'_\pm = \frac{i_\pm}{i_0},$$
$$Q'_\pm = \frac{Q}{Q_0}, \quad Q_0 = \frac{i_0}{4\pi |b_-| n_0}, \quad \zeta = \frac{\alpha}{4\pi e |b_-|}, \quad \nu = \frac{Y}{e i_0}, \tag{4.2}$$

where $Q_0$ and $i_0$ are the characteristic values of particle charge and ion current per particle, yet to be concretized. The primes denoting dimensionless quantities will be omitted below.

On the basis of Eq. (4.2) we can obtain a system of three algebraic equations for determination of equilibrium ion concentrations and particle charge:

$$1 - n_+ n_- - \mu i_+ = 0, \; n_+ - n_- + \zeta \mu Q = 0, \; \nu + i_+ - i_- = 0. \tag{4.3}$$

The equilibrium condition (4.3) for the dispersed medium under consideration is analogous to the Sach equations for ionized gases or the equations of the acting mass law for chemically reactive gas mixtures. Let the distance from the point under consideration to the boundary of the volume occupied by the aerosol be greater than the maximum path length of the particles radiated. Then the local ionization rate $\omega$ is related to the particle concentration $n_p$ and the particle activity by the expression $\omega = n_p C\eta + \delta$ (where $\eta$ is the mean number of ion pairs formed by radiation in a single decay, and $\delta$ is the contribution to ionization from external radiation sources).

From this expression and the definitions of Eq. (4.2) we obtain the relationship between the parameters $\nu$ and $\mu$:

$$\mu = \frac{m}{\nu}\left(\eta + \frac{\delta}{n_p C}\right)^{-1}. \tag{4.4}$$

Only one of the following cases will then be true:

a) $\mu = n_p i_0/\omega \ll 1$, so that in Eq. (4.1) one can neglect the contribution of dispersed particles to the space charge and absorption of gas ions by particles; the equilibrium dimensional ion concentrations are then equal to $n_\pm = \omega^{1/2}\alpha^{-1/2}$ and the problem reduces to that considered in Sec. 2.3

b) $\mu \gtrsim 1$, with the aerosol particle concentration being sufficiently high that within the ion balance equations we must consider the ion fluxes to the particles $i_\pm$. The absolute values of the corresponding electrical currents $\pm e i_\pm$ are much greater than the radioactivity-related current Y. In fact, it follows from Eq. (4.4) with the assumption $m \ll \eta$ and the condition $\mu \gtrsim 1$ that $v \ll 1$. Then in the last expression of Eq. (4.3) we can neglect the quantity v and the values of the dimensionless quantities $n_\pm$, Q are determined by the single parameter $\mu$ (we assume the parameter $\zeta$ fixed). Below we will limit ourselves to consideration of this case.

For diffusion charging of the particles when the condition $eaE/(kT) \ll 1$ is satisfied, it follows from Eq. (2.2) that $i_0 = 4\pi a D_- n_0$, $Q_0 = akT/e$. The characteristic values of $i_\pm$ and Q are relatively small, and as a rule, case "a" is realized. Thus to study the solution of system (4.3) for $\mu \gtrsim 1$ we assume the relationship $eaE/(kT) \gg 1$ satisfied, so that, as follows from Eq. (3.2), $Q_0 = 3a^2E$, $i_0 = 12\pi a^2 |b_-| E n_0$.

For fixed values of $a$, $b_\pm$, $n_0$, $\alpha$, because of the action of the applied electric field the parameter $\mu$ and the characteristic values of Q and $i_\pm$ are much larger than for diffusion charging.

For the ion fluxes to the particle we obtain from Eq. (3.2) dimensionless expressions $i_- = (1 + Q)^2 n_-/4$, $i_+ = (1 - Q)^2 \chi n_+/4$, $\chi \equiv b_+/|b_-|$.

Then from Eq. (4.3) we have an expression to define the equilibrium particle charge

$$v + \chi(\Omega + \sqrt{\Omega^2 + 1})(1 - Q)^2 - (\Omega + \zeta\mu Q + \sqrt{\Omega^2 + 1})(1 + Q)^2 = 0,$$
$$\Omega \equiv -\frac{\mu}{8}[\chi(1 - Q)^2 + 4\zeta Q]. \tag{4.5}$$

After finding the value of Q we calculate the dimensionless ion concentrations with the expressions

$$n_\pm = -\frac{\mu}{8}[\chi(1 - Q)^2 \pm 4\zeta Q] + \sqrt{1 + \Omega^2}. \tag{4.6}$$

Neglecting the small quantity v, for equality of the absolute values of ion mobilities ($\chi = 1$) from Eqs. (4.5), (4.6) we obtain $Q = 0$, $n_\pm = -\mu/8 + \sqrt{1 + \mu^2/64}$. For $\chi \neq 1$ and high $\mu$ values we may use the asymptotic expressions

$$n_+ = \frac{4}{\chi\mu} + o\left(\frac{1}{\mu}\right), \quad n_- = \frac{4}{\mu} + o\left(\frac{1}{\mu}\right), \quad Q = (\chi - 1)(\zeta\chi\mu^2)^{-1} + o\left(\frac{1}{\mu^2}\right).$$

Results of a numerical solution of Eq. (4.5) in the form of a graph $Q'(\mu)$ for parameter values $\chi = 0.7$, $\zeta = 0.5$, corresponding to dry atmospheric air under normal conditions, are shown in Fig. 3. Figure 4 presents curves of the functions $n_\pm(\mu)$ defined by Eq. (4.6). The quantity v was taken equal to zero in the calculations, which, as was noted above, is permissible for $\mu \gtrsim 1$.

Assume that external radiation sources are absent. Then the dimensionless quantities $\mu$, $n_\pm'$, Q' are defined in the following manner:

$$\mu = 12\pi a^2 |b_-| E \sqrt{\frac{n_p}{\alpha\eta C}}, \quad n_\pm' = n_\pm \sqrt{\frac{\alpha}{n_p \eta C}}, \quad Q' = \frac{Q}{3a^2E}. \tag{4.7}$$

We will consider the equilibrium state of an aerosol with particles having a radius $a = 10^{-5}$ m and activity of 500 Bq in an electric field of intensity $2 \cdot 10^5$ W/m. We will assume that the carrier gas is air under normal conditions ($b_+ = 1.3 \cdot 10^4$ m$^2$·V/sec, $b_- = -1.8 \cdot 10^4$ m$^2$·V/sec, $\alpha = 1.6 \cdot 10^{-12}$ m$^3$/sec [9]). We assume that the radioactivity of the particles is determined by beta-decay of strontium atoms $Sr^{89}$ with a mean radiation energy of $9.1 \cdot 10^{-14}$ J. Since the mean energy for ion formation in air is equal to $5.4 \cdot 10^{-18}$ J [10], the quantity $\eta = 1.7 \cdot 10^3$. From Eq. (4.7) and Figs. 3 and 4 we find that $n_p = 10^6$ m$^{-3}$ $\mu = 1$, with equilibrium ion concentrations and particle charge as follows: $n_+ = 6.7 \cdot 10^{11}$ m$^{-3}$, $n_- = 6.4 \cdot 10^{11}$ m$^{-3}$, $Q = 5 \cdot 10^{-16}$ C.

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LITERATURE CITED

1. L. E. Sedov, Mechanics of Continuous Media, Vol. 1 [in Russian], Nauka, Moscow (1976).
2. A. B. Vatazhin, V. I. Grabovskii, V. A. Likhter, and V. I. Shul'gin, Electrogasdynamic Flows [in Russian], Nauka, Moscow (1983).
3. V. D. Ivanov and V. N. Kirichenko, "Spontaneous unipolar charging of 'hot' beta-active aerosol particles," Dokl. Akad. Nauk SSSR, 188, No. 1 (1969).
4. V. N. Kirichenko and V. D. Ivanov, "Kinetics of unipolar charging of 'hot' beta-active particles in an electric field," Dokl. Akad. Nauk SSSR, 188, No. 2 (1969).
5. Ya. I. Frenkel', Theory of Atmospheric Electrical Phenomena [in Russian], GITTL, Moscow–Leningrad (1949).
6. E. J. Whipple and J. A. Chalmers, "On Wilson's theory of the collection of charge by falling drops," Q. J. R. Meteor. Soc., 70, No. 304 (1944).
7. A. V. Bykhovskii and O. M. Zaraev, Hot Aerosol Particles in Technological Applications of Atomic Energy [in Russian], Atomizdat, Moscow (1974).
8. V. D. Ivanov, V. N. Kirichenko, and I. V. Petryanov, "Charging of alpha-active aerosols by secondary electron emission," Dokl. Akad. Nauk SSSR, 182, No. 2 (1968).
9. N. V. Krasnogorskaya, Electricity in the Lower Layers of the Atmosphere and Methods for its Measurement [in Russian], Gidrometeoizdat, Leningrad (1972).
10. B. P. Golubev, Dosimetry and Protection from Ionizing Radiation [in Russian], Atomizdat, Moscow (1976).

# RADIATION OF AN INTENSE SHOCK WAVE IN A FINITE LAYER OF XENON

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UDC 533.6.011+535.231

Strong shock waves in gases are powerful radiation sources [1-3]. During motion of such a shock wave a region of heated gas is formed ahead of the front, which screens the energy of radiation leaving the front surface [1]. This screening effect hinders achievement of high brightness temperatures and radiation fluxes, restricting the possibilities for using intense shock waves as radiation sources.

The experiments of [4] showed that in neon at normal density, brightness temperatures $T = 10^5$ K and radiant flux densities $\Phi = 200$ MW/cm$^2$ can be achieved, although requiring a high (~50 km/sec) shock wave velocity, which can be achieved only by using cascaded equipment [5]. When heavy gases such as xenon and krypton are used high temperatures behind the front can be achieved at lower shock wave velocities but the screening effect which has practically no influence in experiments using neon, because of the high first ionization potential, significantly reduces the maximum values of T and $\Phi$. Thus for xenon at normal density recorded values of T do not exceed $6 \cdot 10^4$ K, with $\Phi - 18$ MW/cm$^2$ [3].

In order to create more powerful radiation sources [6] proposed a method for attenuation of the screening effect by limiting the thickness of the working gas layer through which the powerful shock wave moves. Then after arrival at the target of the heated layer practically all the radiation departing from the shock wave front succeeds in striking the target.

In the present experiments the possibility of attenuating the screening effect was investigated using a strong shock wave moving in xenon with an initial pressure of $3 \cdot 10^3$ Pa. The pressure was chosen so that the characteristic dimensions of the experimental device (Fig. 1) were comparable to the radiation path length in the heated layer. The strong shock wave was generated using an explosive gas compressor 1, then gradually expanded in diffusor 2, arriving in glass tube 3, which contained a diaphragm 4, glass target 5 with strips of aluminum coating of various masses 6, and a mirror 7. The diffusor provided a smooth transition of the shock wave from the compressor to the glass tube, while the diaphragm was used to cut off turbulence near the wall [3]. The mass of the aluminum coating varied from 0.15 to 1.89 mg/cm$^2$. By recording the time of appearance of scintillation at the point where a band of

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