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Abstract

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INVESTIGATION OF THE OPTICAL PROPERTIES OF TRANSPARENT SUBSTANCES AT ULTRAHIGH PRESSURES

When strong shock waves propagate through transparent substances, measurements can be carried out that provide information about the optical properties of a substance compressed to pressures of hundreds of thousands or millions of atmospheres ([1]).

If the width of the shock-wave front is much smaller than the wavelength of light λ, measurement of the intensity of light from an independent source reflected from the surface of the shock wave makes it possible to determine the refractive index n of the compressed substance. In this case the reflection coefficient R, according to the known Fresnel formulas, depends on n of the compressed substance, the known n_0 of the undisturbed substance, and the angle of incidence ψ. This method is also applicable in the case when, after compression, the substance is opaque. When absorption of light in the compressed substance becomes significant already in a layer of thickness λ, in principle it is possible to measure both the real and imaginary parts of n (the imaginary part of n characterizes precisely the absorption of light). For this it is necessary to determine the dependence of R on the angle of incidence and the polarization of the reflected light ([2]). Such a situation arises in the case when compression substantially rearranges the electronic levels of the substance, in particular upon the transformation of a dielectric into a metal by compression ([3,4]).

(Figure: Fig. 1)

Fig. 1. Experimental arrangement. I —incident light; II, III —light reflected from the stationary plexiglass-water boundaries; IV —light reflected from the front of the shock wave in water; V —light reflected from the moving boundary compressed water-compressed plexiglass; AA —plane of contact with the explosive; BB —initial position of the plexiglass-water boundary (dotted line). 1 —plexiglass prism; 2 —water ahead of the shock-wave front; 3 —water compressed in the shock wave.

At not too high a pressure, when the compressed substance remains transparent throughout its entire thickness, its refractive index n can be determined geometrically (see Figs. 1 and 2a), from the path of the rays in the compressed substance. The results of this method are not affected by the width of the shock-wave front, since it is very small in comparison with the thickness of the compressed substance (region 3 in Fig. 1).

As a first example, we have begun an investigation of water and have carried out separate experiments on plexiglass and glass. The arrangement of the experiment for studying the reflection of light from a shock wave in water is shown in Fig. 1. The reflected rays II-V were recorded by a high-speed photochronograph, which, by means of a rotating mirror, swept the phenomenon in time. The setup of the experiment is analogous in the study of plexiglass as well. The glass under investigation was placed in water in such a way that in the experiment reflection of light was observed from the front of the shock wave in the glass and in the water before and after the glass. Typical photochronograms are shown in Figs. 2a, b, and c.

In the substances examined, as can be seen from the streak photographs, reflection of light from the shock-wave front was recorded. In this case compressed water remains transparent throughout the investigated pressure interval from 39 to 144 thousand atm. Glass is opaque at pressures of ~ 200 thousand atm.

Water was investigated in greater detail, since from a single experiment results can be obtained by both methods. For quantitative measurements of the reflection coeffici-

(Figure: Fig. 2)

Fig. 2. *a*—streak photograph of an experiment on reflection of light from the shock-wave front in water (designations as in Fig. 1). *b*—streak photograph of an experiment on reflection of light from a shock wave in Plexiglas; CC—glow of air in the gap when the detonation emerges at the boundary e. e.—Plexiglas. *c*—reflection of light from the front of a shock wave propagating in the system water—glass—water; $IIa, IIIa$—reflection of light from the stationary water—glass boundary; IVa—reflection of light from the shock-wave front in glass; Va—reflection of light from the moving boundary compressed water—compressed glass

ent the width of the image of the reflected rays on the film was specified so as to avoid the influence of nonuniform exposure and photographic blurring. When measuring the intensity of the reflected light, rays II and III served as the standard (Figs. 1 and 2a). In all, 3 series of 4-6 experiments each were carried out. The character of the reflection of light from the surface of the shock wave (see Fig. 2a) corresponds to specular (and not diffuse) reflection, which indicates a high degree of smoothness of the shock-wave front. It follows from the direct data on the coefficients of reflection of light from the shock-wave front that, as the angle of incidence increases from 50 to 75°, the reflection coefficient increases in accordance with the Fresnel relation.

The values of n, together with other parameters of the shock wave, are given in Table 1. The processing of the data by the "geometrical" method of determining n was carried out using the equations of state ([5,6]), with the aid of which, from the shock-wave velocity determined in our experiments, the density to which the water is compressed was calculated. All values of n were determined with a root-mean-square error of ± 0.01. The dependence $n(\rho)$, obtained using the equation of state of water according to ([5]), is given in Fig. 3.

Let us turn to the physical nature of the results obtained. The influence of density and temperature on the refractive index of water near room-

Table 1

No. of point	Calculated according to ([5])	Calculated according to ([6])	n, photom.					
No. of point	ρ, g/cm^3	n, geom.	T, °C	p, thousand atm.	ρ, g/cm^3	n, geom.	p, thousand atm.	n, photom.
1	1.43	1.47	185	39	1.41	1.49	33	1.47
2	1.67	1.53	630	110	1.62	1.56	106	1.52
3	1.75	1.56	875	144	1.83	1.52	150	1.52

at room temperature and at pressures close to atmospheric was given in the work of Raman and Venkataraman ([8])

$$\rho = 0.998\ \text{g/cm}^3; \quad T = 23.1^\circ\text{C}; \quad n = 1.333;$$

$$(\partial n/\partial \rho)_T = 0.325\ \text{cm/g}; \quad (\partial n/\partial T)_\rho = -1.90 \cdot 10^{-5}\ \text{deg}^{-1}.$$

These data, taking into account the refractive index of water vapor, which according to experimental data ([10]) is $n = 1 + 0.33\rho$, may be written as a relation that accounts for the combined effect of density and temperature:

$$n = 1.334 + 0.334(\rho - 1) - 1.90 \cdot 10^{-5} T\rho, \tag{1}$$

where T is in °C.

The refractive index of ice at 0°C, $\rho = 0.9168$, is also consistent with this formula (the mean value $n = 1.311$; according to formula (1), $n = 1.306$).

In the range of densities and temperatures reached at the front of a shock wave in water, the results of calculations by (1) (see Fig. 3) agree satisfactorily with the experimental values of n determined by the geometrical method. Let us note that the solid line in Fig. 3 is slightly curved because of the rise in temperature in the shock wave. Our data confirm a substantial deviation from the Lorentz–Lorenz formula for the dependence $n(\rho)$ (see the dashed line in Fig. 3). This deviation also appeared in earlier experiments by Raman and Venkataraman: for the given $n_{\rho=1} = 1.334$, according to Lorentz–Lorenz one should have

$$\left.\frac{dn}{d\rho}\right|_{\rho=1} = 0.367,$$

whereas in experiment

$$\frac{dn}{d\rho} = 0.325.$$

(Figure: Fig. 3. Dependence of the refractive index on the density of water: a —geometrical, b —photometric method)

Fig. 3. Dependence of the refractive index on the density of water: a —geometrical, b —photometric method

The data obtained by the photometric method for points 2 and 3 lie somewhat below the results obtained by the geometrical method. This can evidently be explained by the finite thickness of the transition layer in which compression of the water occurs. The viscosity of water under normal conditions leads to a shock-wave front width of the order of fractions of an angstrom, at which there should not be any appreciable deviations from the Fresnel formulas. The data of the photometric method can be explained if, following A. G. Oleinik and V. N. Mineev, one assumes that the viscosity of water increases sharply at pressures above $p_k = 60 \div 80$ thousand atm. Then, at pressures p_1 in the shock wave above p_k, one should expect a front structure corresponding to rapid compression from p_0 to p_k and smooth (because of viscosity) compression from p_k to p_1. R. M. Zaidel and V. N. Mineev drew our attention to the latter point. For $p_1 > p_k$ the photometric method is inapplicable, since the refractive index determined photometrically ceases to increase despite the increase of the true $n(\rho_1)$.

The interpretation of the data obtained in processing by means of the equation of state from ([6]) is more complicated. At the same time, in contrast to ([6]), we did not observe a decrease in the intensity of the light reflected from the piston (i.e., twice passed through the compressed water) at pressures exceeding 115 thousand atm. (see Fig. 2a), at which, according to ([6]), a phase transition occurs in water. According to our data, even at pressures of 300 thousand atm. water is still transparent.

In conclusion we note that the reflection method can be applied to solving a number of problems in the physics of high pressures. Thus, in contrast to the results

states (*), the optical method will make it possible to detect not ionic, but electronic conductivity (the convergence of electron bands, approach to the metallic state).

Another possible direction is the study of the smoothness of shock and detonation waves. The latter is essential for solving the problem of detonation of condensed explosives.

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Note: Figure translations are in progress. See original paper for figures.