Academician Ya. B. ZEL' DOVICH, S. B. KORMER, M. V. SINITSYN, and A. I. KURYAPIN

1958

SovietRxiv

Abstract

Full Text

PHYSICS

Academician Ya. B. ZEL' DOVICH, S. B. KORMER, M. V. SINITSYN, and A. I. KURYAPIN

TEMPERATURE AND HEAT CAPACITY OF PLEXIGLAS COMPRESSED BY A SHOCK WAVE

Compression by a strong shock wave is a means of obtaining high pressures and high temperatures unattainable by other methods.

Shock compression of gases leads to states with high temperature but low density. The thermodynamic properties of such states can be completely calculated theoretically. Therefore, in the case of gases, the principal interest lies in the more complex questions of the structure of the thin layer in which, in the shock wave, the transition from the initial state to the final state takes place; questions of the mechanism and time of establishment of thermodynamic equilibrium; the rate of excitation, dissociation, and ionization. A review of work on shock compression of gases and references to the original literature are given in ([1]).

In the case of shock compression of liquids and solids, a density is reached that exceeds their initial density by several times and the density of compressed gases by hundreds of times. If the temperature is then below 100,000°, the interaction of atoms, ions, and electrons in the compressed state is not small in comparison with the energy of their thermal motion. Theoretical calculation of the pressure, energy, and other thermodynamic quantities of such a state appears practically impossible. All the more important, therefore, is the experimental investigation of a substance compressed by a shock wave.

If one confines oneself only to measurements of the wave velocity and the velocity of motion of the compressed substance, then the density, pressure, and energy of the substance can easily be found, but calculation of the temperature ([2]) presents great difficulties and can hardly be carried out with acceptable accuracy. Investigation of transparent bodies makes it possible to measure directly the temperature from the brightness of the radiation of the substance compressed by the shock wave. After strong compression, at which a temperature of several thousand degrees is reached, owing to displacement of electronic levels and excitation of electrons, the substance, initially transparent, becomes opaque and radiates intensely.

The radiation of the shock-wave front was observed through a layer of still uncompressed transparent substance and was recorded with high-speed photochronographs in two regions of the spectrum: blue (λ = 4020 Å) and red (λ = 6000 Å). The measurement procedure is similar to that used by I. Sh. Modelem ([3]).

The temperature was determined in polymethyl methacrylate $(C_5H_8O_2)_n$ (plexiglas) with an initial density of 1.18 g/cm^3 under conditions in which the shock-wave velocity was 16.5 km/sec. In the compressed state the density is 3.15 g/cm^3, and the pressure is $2 \cdot 10^{12}$ dyn/cm^2*.

On the basis of three experiments the following quantities were obtained: the brightness temperature, measured from the intensity of the radiation in the red re-

* According to measurements by A. A. Bakanova.

region, 8300 ± 500°K, and the color temperature, determined from the ratio of intensities in the red and blue regions of the spectrum, 11000 ± 1000°K.

Taking the energy of Plexiglas in the initial state to be zero, we find the energy of compressed Plexiglas

$$E = \frac{1}{2}P(V_0 - V) = 0.53 \cdot 10^{12} \text{ erg/g}.$$

If the atoms were in the state of an ideal gas at a temperature of 8300°K and a density of 3.15 g/cm^3, their pressure would be $\rho NkT = 0.33 \cdot 10^{12}$ dyn/cm^2, and the thermal energy would be $\frac{3}{2}NkT = 0.16 \cdot 10^{12}$ erg/g (N is the number of atoms in 1 g).

In accordance with the views developed by L. D. Landau and K. P. Stanyukovich [4] as applied to detonation explosion products, let us assume that in the case of compressed Plexiglas the greater part of the pressure is elastic pressure, and the motion of the atoms should be regarded as vibrations. Then the thermal pressure is approximately $4\rho NkT = 1.3 \cdot 10^{12}$ dyn/cm^2.

The thermal energy of the atomic vibrations is $3NkT = 0.31 \cdot 10^{12}$ erg/g. We find the elastic pressure as the difference between the total and thermal pressures, i.e. $0.7 \cdot 10^{12}$ dyn/cm^2. Since in this case the elastic pressure turns out to be of the same order as the thermal pressure, the calculations given below are only approximate.

Taking the dependence of the elastic pressure on density to be

$$P_y = a(\rho^3 - \rho_0^3), \qquad \text{where } \rho_0 = 1.18 \text{ g/cm}^3,$$

we find the elastic energy

$$E_y = \frac{a(\rho - \rho_0)^2(2\rho_0 + \rho)}{2\rho} = \frac{1 + \alpha - 2\alpha^2}{1 + \alpha + \alpha^2}\frac{P_y}{2\rho}, \qquad \text{where } \alpha = \rho_0/\rho.$$

Then, for $P_y = 0.7 \cdot 10^{12}$ dyn/cm^2, we obtain $a = 0.024 \cdot 10^{12}$ cm^3/g$^2 \cdot$ s^2, $E_y = 0.08 \cdot 10^{12}$ erg/g.

The elastic part of the pressure is close to the pressure of the explosion products of trotyl, extrapolated according to the law $P_y = a\rho^3$ [4] to the density of compressed Plexiglas.

In the energy balance, after subtracting the thermal and elastic energies, approximately $0.14 \cdot 10^{12}$ erg/g remains. This energy was expended in breaking chemical bonds. For comparison, let us note that the transformation of $C_5H_8O_2$ into C_{solid}, H_2, and H_2O proceeds almost without a change in energy; transformation into C_{solid}, H_2, and O_2 requires about $0.055 \cdot 10^{12}$ erg/g; transformation into C_{solid}, H and O atoms requires $0.26 \cdot 10^{12}$ erg/g; transformation into H, O, and C atoms requires $0.62 \cdot 10^{12}$ erg/g. Consequently, under compression conditions a profound destruction of the molecule occurs, but there is not enough energy for complete rupture of all chemical bonds.

Altogether, the thermal and chemical energy of compressed Plexiglas at 8300°K, equal to approximately $0.45 \cdot 10^{12}$ erg/g, is 3.5 times greater than the energy calculated from the heat capacity of Plexiglas under normal conditions at room temperature, 0.365 cal/g $\cdot$ deg $= 1.53 \cdot 10^7$ erg/g $\cdot$ deg.

At a density of about 3 g/cm^3, the very concepts of separate molecules apparently are not applicable.

In the compressed state, the distance between neighboring atoms is of the same order as in a chemical compound. Therefore, dissociation can be spoken of only conditionally—not in the sense of separation of atoms, but in the sense of the transition of electrons into excited states corresponding to the repulsion of atoms.

The study of the compression of transparent bodies by optical methods is being continued by us at the present time. When measuring temperature by radiation, it is necessary to introduce a correction for the reflection of light from the shock wave, i.e. from the boundary between compressed and uncompressed material. This is indicated by the presence of a noticeable difference between the measured color and brightness temperatures.

The study of the reflection of light emitted by the compressed substance, by differences in brightness temperatures, and a direct study of the reflection of light from an independent source by the shock wave, should yield very interesting information on the refractive index and the coefficient of absorption of light by the compressed substance. Ultimately, carrying out such measurements on various substances may lead to clarification of the influence of density on the electronic levels of condensed bodies.

We take this opportunity to express our gratitude to L. V. Al' tshuler, I. Sh. Model' , and Yu. P. Raizer for their constant interest in this work.

Received
4 VI 1958

REFERENCES

1. Ya. B. Zel' dovich, Yu. P. Raizer, *Uspekhi fizicheskikh nauk*, **63**, issue 3, 613 (1957).
2. Ya. B. Zel' dovich, *ZhETF*, **32**, 1126 (1957).
3. I. Sh. Model' , *ZhETF*, **32**, 714 (1957).
4. L. D. Landau, K. P. Stanyukovich, *DAN*, **46**, No. 9, 339 (1945).

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