Measurements of the optical emission of a dense bismuth plasma during its adiabatic expansion

S. V. Kvitov, A. V. Bushman, M. I. Kulish, I. V. Lomonosov,
A. Ya. Polishchuk, A. Yu. Semenov, V. Ya. Ternovoĭ, A. S. Filimonov,
and V. E. Fortov
Institute of Chemical Physics, Academy of Sciences of the USSR, 142432, Chernogolovka

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Experiments have been carried out to detect the optical emission from a collisional bismuth plasma produced upon the emergence of an intense shock wave at a free surface. The results are reported. The observed temperature is compared with temperatures calculated from various models of a dense collisional plasma.

The behavior of a dense, collisional metal plasma in the supercritical region of parameter values—in an intermediate region between a solid and an ideal gas—is presently attracting much interest because of the major uncertainty in theoretical predictions of the probability for the occurrence of "plasma" phase transitions and because of the extremely limited possibilities of steady-state experiments, which are capable of no more than measuring the properties of low-temperature mercury, cesium, and rubidium plasmas.[1] In order to go beyond static experiments, it is necessary to generate some extremely high energy densities (more than a few kilojoules per cubic centimeter) during the compression and irreversible heating at the front of an intense shock wave, followed by an expansion of the shock-compressed medium in an isentropic rarefaction wave.[2,3] In this case it becomes possible to measure the thermodynamic properties which must be known in order to construct equations of state valid over wide regions. From the physical standpoint, there is much interest in an experimental study of optical phenomena accompanying the emergence of an intense shock wave at a free surface.[4] Such a study would provide information of interest on optical properties which are intimately related to the structure, composition, and electron-energy spectrum of the expanding plasma.

In this letter we are reporting the results of our first experiments carried out to detect the optical emission from a collisional bismuth plasma produced upon the emer-

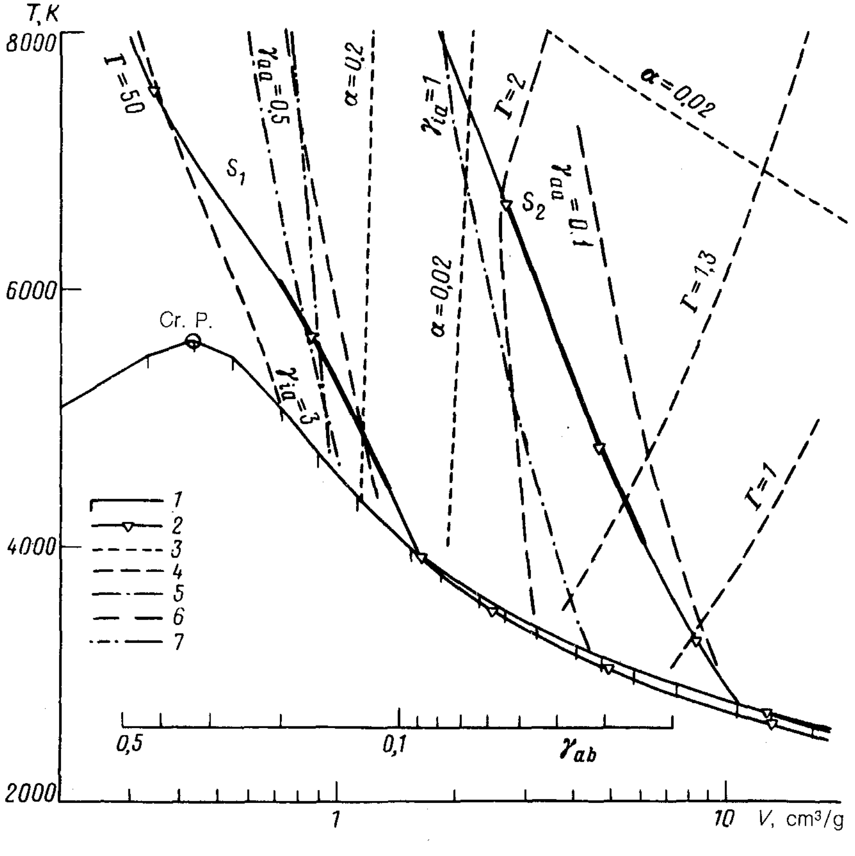

FIG. 1. T, V diagram of bismuth. 1—Boundary of two-phase region; 2—S_1 and S_2; 3—$\alpha = \text{const}$; 4—$\Gamma = \text{const}$; 5—$\gamma_{ia} = \text{const}$; 6—$\gamma_{aa} = \text{const}$; 7—$\epsilon_f/(kT) = 1$.

gence of an intense shock wave, with a pressure of several million atmospheres, at a free surface. The intense shock waves were excited by explosive "compressional" striker devices, in which thin molybdenum liners (0.2 and 0.1 mm thick) were accelerated to velocities of 7.0 and 8.3 km/s by the "gradient compression" effect.[2] When such liners strike a target 0.16 or 0.19 mm thick, they excite shock waves with peak pressures of 2.8 and 3.6 Mbar in the bismuth. The emergence of the shock waves at the free surface of the sample leads to an adiabatic expansion of a dense plasma. The optical emission from this plasma is detected by fast photodetectors (with a time resolution $\simeq 10$ ns, $\lambda = 700 \pm 5$ nm). The motion of the plasma itself is detected by high-speed image converters.

The states of a collisional plasma which were realized in the experiments are illustrated in Fig. 1 in the T, V (temperature, volume) plane. Shown here, along with the boundary of the two-phase region according to Ref. 5 (line *1*), are the isentropes S_1 ($P_H = 2.8$ Mbar) and S_2 ($P_H = 3.6$ Mbar). The regions of states which were detected experimentally are marked. Contour curves of the degree of ionization

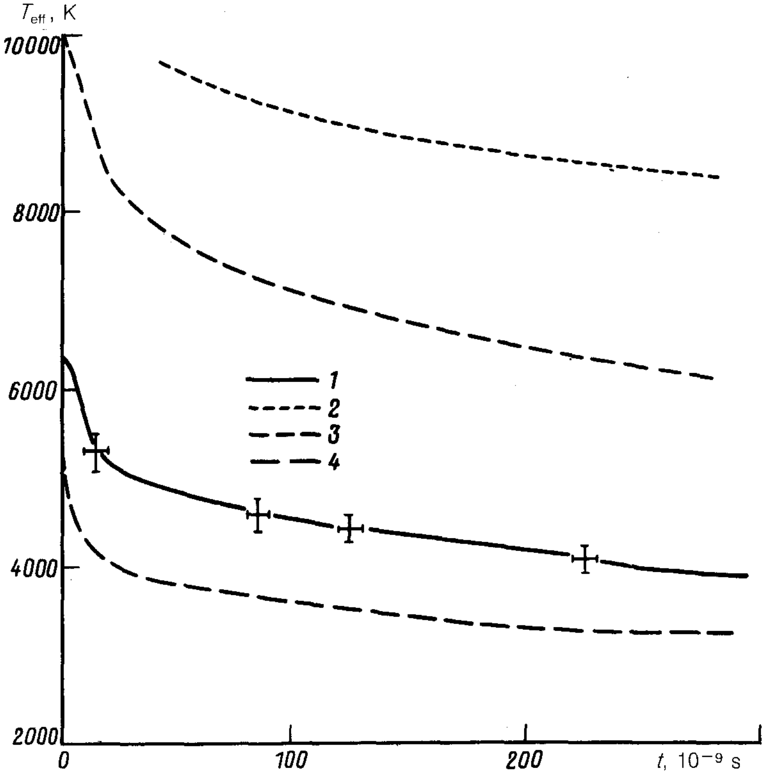

FIG. 2. Plot of $T_{\text{eff}}(t)$ for the surface of rarefaction wave S_1 ($P_H = 2.8$ Mbar). 1—Experimental data (with error bars); 2—calculation from the Unsöld-Kramer formula; 3—calculation from Ref. 6, incorporating only the bremsstrahlung absorption mechanism; 4—calculation from Ref. 6, with both bremsstrahlung and photoionization.

$\alpha = n_e/(n_i + n_a)$, of the degree of Coulomb collisionality $\Gamma = (8\pi n_e)^{1/2}e^3/(kT)^{3/2}$, and of the ion-atom interaction intensity $\gamma_{ia} = (2\pi \alpha e^2 N)/(r_a kT) \simeq 1$ $\{\alpha \simeq 50a_0^3$ is the polarizability of the neutrals; the atomic radius is $r_a \simeq 3a_0 = 3h^2/[m_e(2\pi e)^2]\}$ were calculated from a plasma model incorporating degeneracy, the interaction of charges with each other and with neutrals, and the intrinsic dimensions of the atoms and ions.[6] We see that the states detected in the adiabatic-rarefaction waves correspond to a dense, cool plasma with a strong Coulomb interaction, $\Gamma \simeq 1.3$–30, with a change in statistics near the curve $\epsilon_f/kT = (3n_e/\pi)^{2/3}h^2/(8m_e kT) = 1$ and with a significant polarized interaction of the charges with the neutrals, $\gamma_{ia} \simeq 0.5$–3. Since the states which are realized in the rarefaction wave are close to the boiling point, the interaction of the neutrals described by the van der Waals parameters a and b is also important under these conditions: $\gamma_{aa} = (\mathrm{Na})/(kT) \simeq 0.2$–$1$, $\gamma_{ab} = 3\mathrm{Nb} \simeq 0.03$–$0.3$.

On the oscilloscope traces which were recorded we find a narrow emission peak (about 20 ns wide), which is caused by the shock-compressed plasma. Then comes a relatively slow decay of the emission intensity which is a consequence of a cooling of the plasma in the centered rarefaction wave. The intensity of the optical radiation emitted from the expanding plasma is found through a joint solution of the hydrodynamic equations and the radiation transport equation. The results of these calculations are shown in Figs. 2 and 3. They support the estimates of Ref. 4, according to which

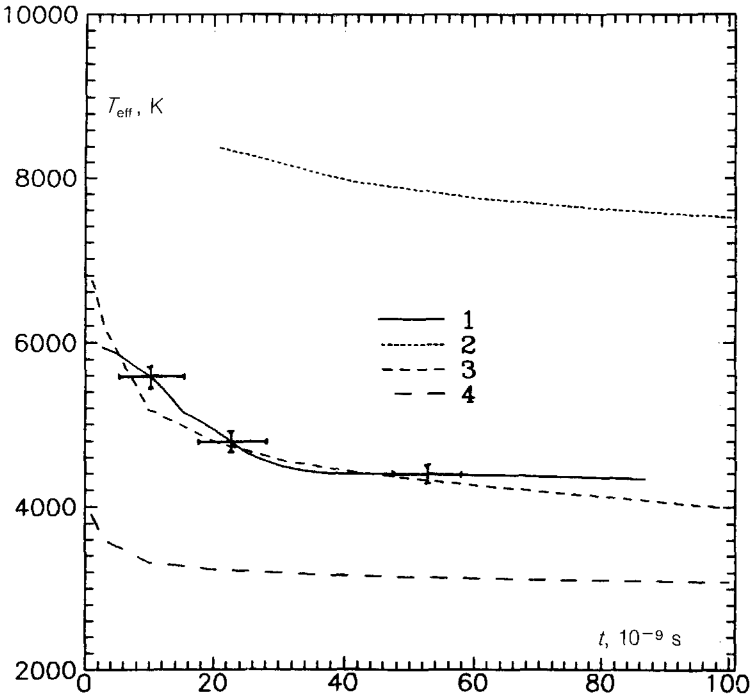

FIG. 3. Plot of $T_{\mathrm{eff}}(t)$ for the surface of rarefaction wave S_2 ($P_H = 3.6$ Mbar). The notation is the same as in Fig. 2.

the radiation is effectively that of a plasma slab at a unit distance ($\int_0^x \kappa_\nu dx = 1$) along the path of the optical radiation from the vacuum boundary. This condition can be used along with (a) the semiempirical equation of state[5] which has been constructed previously from experimental data and (b) the experimental $T_{\text{eff}}(t)$ dependence to draw conclusions about the plasma absorptivity κ_ν. Because of the extremely strong dependence of κ_ν on the parameters of the state (this dependence is exponential in T), the values of T_{eff} found experimentally are actually determined by local values of κ_ν, which pertain to this effective radiating slab.

The strong interparticle interaction illustrated by Fig. 1 complicates attempts to carry out a systematic theoretical analysis of the composition and optical properties of such plasmas. We are obliged to resort to simplified models. Line *2* (in Figs. 2 and 3) corresponds to a calculation of κ_ν from the Unsöld–Kramer formula[1,4] with allowance for photoionization of the high-lying excited states and for inverse bremsstrahlung in the fields of the ions and neutrals at a fixed degree of ionization of the plasma, $\alpha = 1$. Lines *3* and *4* show results calculated for the absorption coefficient on the basis of a hydrogen-like model of the bismuth atom.[6] We see that at low densities and small values of the collisionality parameter S_2 (Fig. 2) a detailed account of the ionization processes makes it possible to reach a reasonable agreement with experiment, despite the extremely crude description of radiative bremsstrahlung processes (line *3* in Fig. 2) and photoionization processes (line *4* in Fig. 2) in κ_ν. For the adiabat S_1 (Fig. 3) the plasma density is about an order of magnitude higher than that on S_2; this circumstance degrades the agreement between experiment and the simple models. In particular, it provides evidence that photoionization processes are less important in the compressed plasma. It is possible that here, as in Ref. 7, we are seeing a "bleaching" of the plasma as a result of the transition of some of the high-lying energy levels into the continuum with increasing plasma density.

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