Shock compression and adiabatic decompression of a dense bismuth plasma at extreme thermal energy densities

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Experimental results on the shock-wave compression of solid and porous bismuth samples at pressures over the range 0.4–6 Mbar are reported. The course of the supercritical decompression isentropes between a highly compressed condensed state and a low-density plasma has been determined. The experimental results are used to write a thermodynamic description of the high-energy states of a dense bismuth plasma.

The behavior of a substance at extremely high pressures and temperatures is of interest both for analyzing the processes which occur when intense pulses of some agent are applied and for drawing a picture of the fundamental characteristics of a medium over a broad region of the phase diagram for states with a high thermal energy density. While the theoretical description of the thermodynamics of metals runs into no particular difficulties at ultrahigh pressures or low densities,[1] the region which lies between the highly compressed metallic liquid and the gaseous plasma is the region of the greatest uncertainties in the theoretical predictions and a region of a nearly complete absence of experimental data.

In this paper we report a study of the thermodynamics of a dense bismuth plasma by dynamic shock-compression methods at the front of an intense wave and isentropic expansion of shock-compressed states.[2] Following the recommendation in Ref. 3, we first made a continuous record of the supercritical transition of the metal from extremely hot condensed states at pressures in the range 0.4–6 Mbar to states of a low-density, slightly collisional plasma.

The idea of Ref. 3 can be implemented only at high values of the entropy of the shock compression, and it requires extremely intense shock waves.[4] This extremely high intensity can be reached by using multistage, layered, explosive-driven, energy-compression ("cumulative") striker systems. The action of each stage of the system is based on the organization of an elastic collision of layers of materials with a high dynamic rigidity and decreasing thickness through an intermediate layer of a material with a low dynamic rigidity. The use of polymers as easily compressible layers and plastic explosives made it possible to accelerate molybdenum strikers 0.1–0.2 mm thick to velocities[5] of 8–12 km/s, which correspond to a mass velocity of the bismuth in the shock wave of 4–6 km/s (the $m = 1$ shock adiabat in Fig. 1) and to a velocity of the metal in the wave of the isentropic decompression of 10–16 km/s (isentropes S_3–S_6). In several experiments, an additional increase in the irreversibility effects of the shock compression was achieved by another method: The bismuth was a finely dis-

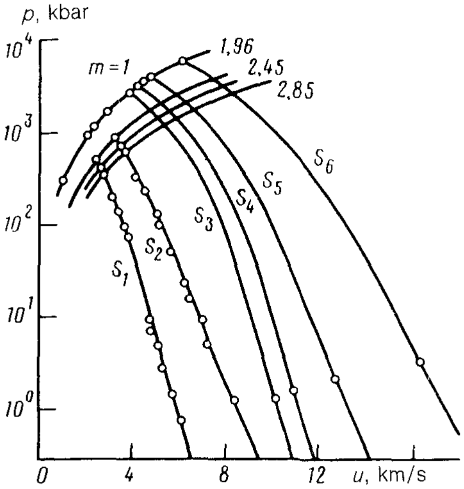

FIG. 1. Dynamic experiments on the high-energy states of a dense bismuth plasma. p, u—The pressure and mass velocity in bismuth samples during shock-wave loading and in the isentropic decompression waves; m—shock adiabats of samples with various initial porosities; S—decompression isentropes. Points—experimental; solid lines—calculated.

persed powder with an initial porosity $m = \rho_0/\rho_{00} = 1.96, 2.45, 2.85$ (the shock adiabats of the porous samples and isentropes S_1 and S_2 in Fig. 1).

The properties of the bismuth plasma during its shock-wave compression were measured by methods of deceleration and reflection.[6] The corresponding electrical and optical signals were detected by high-speed oscilloscopes and image-converter cameras. The states of reduced density (of density lower than that of a solid) were detected by the method of isentropic expansion of the shock-compressed metal into media with a lower dynamic rigidity and know shock adiabats[7,8]: polymers, air, and argon compressed beforehand to 1–30 bar.

The present experiments (Fig. 1) have made it possible to raise the upper limit on the pressure on the shock adiabat of bismuth of normal density from 3.4 Mbar to 6.1 Mbar. For the first time, shock wave data have been obtained on porous samples, and data on the isentropic expansion of a dense bismuth plasma have been obtained. An important point is that in the experiments which have been carried out to date[5,7,8] the states in the decompression waves have corresponded to the liquid-metal phase, only partially involving the near-critical region and the evaporation curve. In the present experiments we have been able to achieve states far in the supercritical region and to follow the thermodynamic properties from a highly compressed ($\rho = 2.6\rho_0$) degenerate phase with pressures in the megabar range all the way to quasi-ideal Boltzmann gaseous plasma of low density ($\rho \sim 10^{-2}\rho_0$). In a single series of experiments, we covered a range of thermodynamic states spanning three orders of magnitude in the density and four in the pressure.

In this region of parameter values, which presents formidable difficulties both theoretically and experimentally,[1,2] some complex and varied physical phenomena unfold as the plasma expands: A collisional plasma with an appreciable particle-particle interaction is produced. The degeneracy of the electrons is lifted, and they undergo recombination. The energy spectrum changes. A metal-insulator transition occurs, with possible first-order plasma phase transitions.[2,9] The experimental results obtained by us do not reveal any definite indications of the appearance of such exotic phase transitions. The inflection points on the lower parts of the isentropes in Fig. 1 are a consequence of the passage of these curves directly above the critical point.

These experimental results have been used to construct a wide-range semiempirical equation of state for bismuth, by the method of Refs. 8 and 10. The equation of state determines the thermodynamic characteristics of the metallic plasma, reproduces the effects of high-temperature melting and evaporation, and has the correct high-energy asymptotes. The quality of the calculations from this equation of state can be seen in Fig. 1, where the calculated results are compared with data from dynamic experiments.

The entropy diagram in Fig. 2 shows the calculated shock adiabats and phase boundaries. Experimental data characterizing the part of the phase plane covered in the experiments are shown. Also shown are curves of constant value of the degree of ionization α and the Coulomb collisionality parameter $\Gamma = \sqrt{4\pi n}(e^2/kT)^{3/2}$ according to plasma calculations in the ring approximation with the canonical grand ensemble of statistical mechanics.[11] We see that the adiabatic decompression from the highest-energy state, B, with an entropy $S_B = 0.74$ J/(g·K) leads to a low-density plasma with the parameter values $\alpha \approx 0.1$ and $\Gamma \approx 1$ in the final state, A. Under these conditions the equilibrium properties of the plasma can be calculated sufficiently reliably by the standard methods of statistical physics.

By virtue of the isentropic nature of the flow, the calculated entropy S_A must be equated to the entropy of the shock-compressed bismuth at megabar pressures in state B. This procedure makes the dynamic method thermodynamically closed.[3] The calculation of Ref. 11 yields a plasma entropy $S_A = 0.76$ J/(g·K), which is close to the value S_B found from the semiempirical equation of state. This additional and important control method is evidence for the validity of the thermodynamic description of

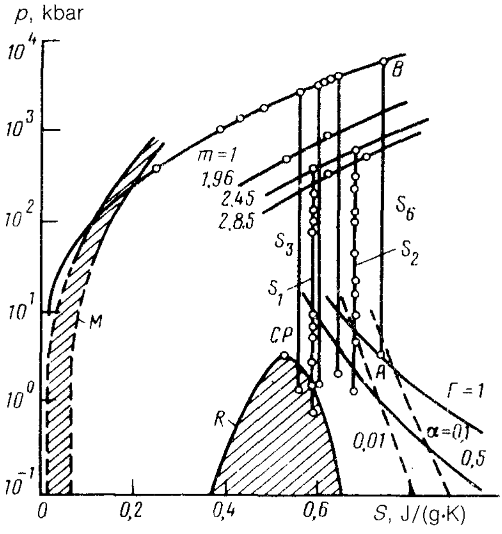

FIG. 2. Entropy diagram of bismuth. M—Melting region (at low pressures, the melting of the metastable high-pressure phase BiVI is shown, because of the complex picture of structural transitions in bismuth); R—line of the liquid-vapor equilibrium with the critical point (CP); α—degree of ionization; Γ—the Coulomb collisionality parameter. The notation is otherwise the same as in Fig. 1.

states with extremely high thermal energy densities. It makes it possible to generate through small corrections based on all the experimental isentropes, an exhaustive description of the thermodynamic characteristics of bismuth over a broad part of the phase diagram.

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