Dynamic compressibility and thermodynamics of a dense aluminum plasma at megabar pressures

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The dynamic compressibility of a dense aluminum plasma has been measured over the pressure range 2–4 Mbar. The characteristics of the adiabatic expansion of shock-compressed aluminum were measured simultaneously. A semiempirical, wide-range equation of state is proposed for describing the results of the dynamic experiments.

In order to analyze physical effects and the dynamics of matter at high local levels of the energy evolution, we need information on the thermodynamic properties of hot and compressed metal liquids and dense plasmas under conditions such that the interparticle interaction is important. These deviations from an ideal plasma complicate a purely theoretical description[1] and motivate experiments in the megabar pressure range.

A dense aluminum plasma was produced in the present experiments by one- and two-stage multilayer focused-explosion ("cumulative") systems.[2,3] Chemically active and inert inserts of an easily compressed material were used, so that molybdenum strikers 0.1–0.2 mm thick could be accelerated to 8–13 km/s. The total energy evolution in an experiment was about 5 MJ, and the local radius of curvature of the incident molybdenum striker was about 40 cm. In each experiment an Agat SF image converter was used to record the striker velocity (W_{Mo}), the velocity (D) of the shock wave in a specially shaped aluminum target with an overall thickness of about 0.5 mm, and the velocity (D_a) of the shock wave in atmospheric air during the expansion of the material of the sample. The velocity (u) of the shock-compressed plasma was found by a stopping method from the known shock adiabat of molybdenum[4] and the measured values of W_{Mo} and D. The wave velocity D_a found experimentally was used with the standard shock adiabat of air to determine the characteristics of the isentropic expansion wave: the mass velocity W^S and the pressure p^S.

The degenerate plasma states that were produced (Fig. 1) fall in the range of parameters in which an electronic phase transition has been predicted on the basis of previous experiments.[5] The experimental points found on the shock adiabat of aluminum indicate that the plasma is only slightly compressible over the density range studied, and they show no indication of any anomalous features which might be attributed to a substantial redistribution of electrons among shells during the compression. These new results are furthermore consistent on the low-pressure side with data from experiments with pneumatic and explosive shock-wave sources,[6,7] while on the side of ultrahigh pressures they agree with the results of some unique measurements of the absolute compressibility[8] and some data obtained by US researchers from under-

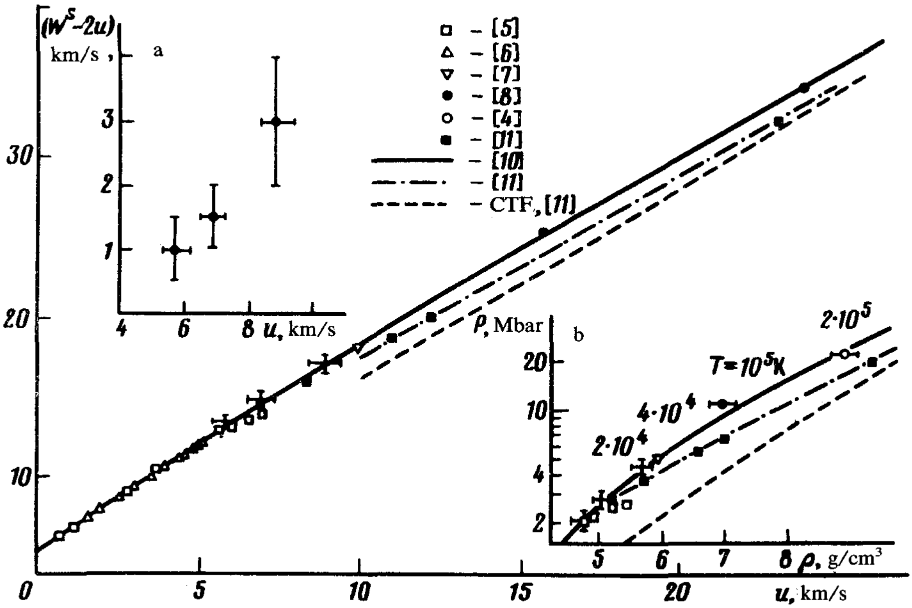

FIG. 1. Shock adiabat of aluminum. The points with the error bars are the experimental results. a—Velocity in the isentropic rarefaction wave; b—p-ρ diagram for the high-pressure region.

ground nuclear explosions.[4] It thus becomes possible to describe the dynamic experiments of Refs. 4 and 6–8 and the present measurements in a noncontradictory way by a smooth curve, which shows that electronic transitions have no effect on the plasma compressibility over the broad ranges of pressures and densities that have been studied. We might note that the new results on the compressibility of an aluminum plasma shown in Fig. 1 are in reasonable agreement with results calculated from a quantum-mechanical model of augmented plane wave,[9] which also predict no phase transition in this region.

The detection of thermodynamic states, which arise during the adiabatic expansion of a metal compressed beforehand and irreversibly heated at the front of an intense shock wave, has made it possible, for the first time, to determine the properties of a dense degenerate aluminum plasma. It has thus become possible to advance into the region of a highly heated metal liquid—a region that poses difficulties for both experiment and theory. An analysis based on the new results (Figs. 1a and 2) shows that the plasma states detected have densities lower than those of a solid ($\rho/\rho_0 \approx 0.5$) and are extremely high-temperature states, near the high-temperature evaporation curve and the critical point of aluminum. These results constitute evidence that there are no phase transitions caused by a strong Coulomb interaction at the metal-insulator transition[1] in a nonideal plasma.

The results on the adiabatic expansion, have been used along with data on the shock compressibility of solid and porous samples and a series of static measurements to construct a wide-range equation of state for aluminum[10] Figure 1b demonstrates

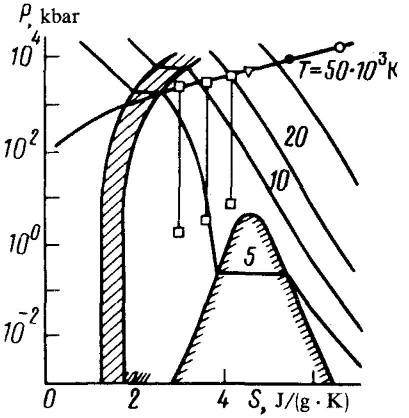

FIG. 2. Pressure-entropy diagram for aluminum. Shown here are states in the shock-compression wave and the isentropic rarefaction wave. The hatching shows the melting region and liquid-vapor equilibrium line.

how well this semiempirical equation of state describes the dynamic experiments at pressures up to ~20 Mbar. Shown for comparison here are shock adiabats calculated from the corrected Thomas-Fermi theory and the results of comparative interpretation of the compressibility of aluminum and silica gel on the basis of the interpolation of Ref. 11. We see that the alternative descriptions of the dynamic characteristics of the dense aluminum plasma under these exotic conditions yield much poorer results; the discrepancy with experiment reaches a factor of 1.5–2 in terms of the pressure.

[1] V. E. Fortov, Usp. Fiz. Nauk **138**, 361 (1982) [Sov. Phys. Usp. **25**, 781 (1982)].

[2] V. Ya. Ternovoĭ, in: Nestatsionarnye problemy gidrodinamiki (Dinamiki sploshnoĭ sredy v 48) (Time-Varying Hydrodynamic Problems; Fluid Dynamics, No. 48), Institut gidrodinamiki SO AN SSSR, Novosibirsk, 1980, p. 141.

[3] A. G. Ivanov, M. V. Korotchenko, E. Z. Novitskiĭ, V. A. Ogorodnikov, B. V. Pevnitskiĭ, and S. Yu. Pinchuk, Zh. Prikl. Mekh. Tekh. Fiz. **2**, 86 (1982).

[4] C. E. Ragan, Phys. Rev. **A25**, 3360 (1982).

[5] L. V. Al'tshuler and A. A. Bakanova, Usp. Fiz. Nauk **96**, 193 (1968) (*sic*).

[6] A. C. Mitchell and W. J. Nellis, J. Appl. Phys. **52**, 3363 (1981).

[7] S. B. Kormer, A. I. Funtikov, V. D. Urlin, and A. N. Kolesnikova, Zh. Eksp. Teor. Fiz. **42**, 686 (1962) (*sic*).

[8] L. P. Volkov, N. P. Voloshin, A. S. Vladimirov, V. N. Nogin, and V. A. Simonenko, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 623 (1980) [JETP Lett. **31**, 588 (1980)].

[9] A. K. McMahan and M. Ross, in: High Pressure Science and Technology (K. D. Timmerhaus and M. S. Barber, eds.) Plenum Press, New York, Vol. 2, 1979, p. 726.

[10] A. V. Bushman and V. E. Fortov, Usp. Fiz. Nauk **140**, 177 (1983) [Sov. Phys. Usp. **26**, 478 (1983)].

[11] L. V. Al'tshuler, N. N. Kalitkin, L. V. Kuz'mina, and B. S. Chekin, Zh. Eksp. Teor. Fiz. **72**, 317 (1977) [Sov. Phys. JETP **45**, 167 (1977)].

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