Lawrence Livermore Laboratory

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LLL Dynamic High Pressure Experiments

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The Lawrence Livermore Laboratory has several experimental facilities to measure material properties at dynamic high pressures. These include an isobaric expansion experiment, a two-stage light-gas gun, and a high-power laser facility (Janus). Each of these will now be briefly described.

I. Isobaric Expansion Experiment

The isobaric expansion experiment is a technique which gives the simultaneous measurement of specific enthalpy up to 1 MJ/kg, temperature up to 7000 K, specific volume up to fourfold expansion, and electrical resistivity at constant pressures up to 0.5 GPa (5 kbar) of inert Ar gas. In addition the heat of fusion, bulk thermal expansion, and specific heat, C_p , are also obtained for hot expanded liquids.¹

A metal cylinder is heated by passage of electrical current. The sample is constrained axially so that the resulting decrease in density causes an increase in the radius. Sample volume is determined by casting a shadow of the cylinder and recording the diameter of the shadow as a function of time. Enthalpy is obtained by monitoring sample current and the voltage across a central length of the cylinder and calculating the energy deposited per unit

time. The combination of sample voltage, current, and volume are used to obtain the electrical resistivity. The temperature is measured with a three-channel optical pyrometer to record the thermal radiation emitted from the sample. The experiment is illustrated in Fig. 1.

The time scale of the experiment is a few tens of microseconds. This time is short enough for the liquid column to remain stable and long enough for sound waves to reverberate through sample and gas to maintain constant pressure. The current pulse is also long enough so that the material is uniformly heated; i.e., the skin effect is small.

Data has been obtained for W, Mo, Nb, V, Ir, Pt, Pb, U, C, Ta, and the alloys Au-10% Cu, Nb-10% Hf, Ta-10% W. The volume thermal expansion of lead² as a function of temperature is shown in Fig. 2. The electrical resistivity of expanded lead² as a function of relative volume is shown in Fig. 3.

II Two-Stage Gun

The LLL two-stage gun accelerates 20g projectiles to velocities up to 7 km/s.³ On impact the projectile and target are compressed and irreversibly shock-heated causing a rapid increase in pressure. In condensed matter shock pressures ranging from 20GPa (200 kbar) for low density materials like liquid deuterium up to 500 GPa (5 Mbar) for high density materials like Ta can be achieved by a single shock. Compressions range over factors of 1.5-3.5 and temperatures can reach 3 eV in very compressible materials. On isentropic release from strong shock pressures matter can be studied in the range of 0.1 GPa (1 kbar), 20 percent expansion from normal density, and temperatures of a few thousand degrees. Ar gas can be shocked to 5 GPa (50 kbar), densities of 0.2 g/cm³, and temperatures of about 5 eV.

The two-stage gun is illustrated in Fig. 4. It consists of a breach containing up to 1.35 kg of gun powder, a pump to be filled with hydrogen, and an evacuated barrel for guiding the projectile to the target. Hot gases from the detonated gun powder drive a 6.8 kg piston into the 90 mm-i.d. pump tube. The piston compresses about 30 moles of hydrogen gas, the second-stage driving medium, to about 140 MPa before the gas breaks a rupture value and accelerates the 20 g projectile down the 28 mm-i.d., evacuated barrel to a muzzle velocity of up to 7 km/s. High pressures and temperatures are achieved on impact of the projectile with a target.

This facility can be used to make accurate equation of state measurements. Pressure, specific volume, and specific energy, can be obtained by measuring shock and material velocities and initial material densities. The Hugoniot relations which are derived on the basis of conservation of mass momentum, and energy can then be used to obtain the above thermodynamic properties from the measured data. Other measurements include electrical conductivity and temperature. Lattice parameters can be measured with flash x-ray diffraction on a 10 ns time scale. All these measurements are performed on materials in a precisely defined thermodynamic state.

The shock pressure of Ar as a function of relative volume⁴ is shown in Fig. 5. Ross has shown that the data at low pressures can be understood in terms of an intermolecular repulsion between Ar atoms.⁵ At lower volumes, however, the pressure increases slower than would be predicted by the extrapolation of this model. This behavior is explained by Ross in terms of the thermal excitation of electrons across a volume-dependent energy gap. That is, the shock energy is being absorbed in electronic excitation rather than simply producing thermal pressure.

The electrical conductivity of water has been measured to shock pressures of 600 kbar. The rapid increase in conductivity with shock compression is probably due to molecular ionization of H_2O into H_3O^+ and OH^- .

III Janus Laser

A high energy, ultrashort, light pulse is focused down to a small spot on a sample surface. A high-pressure shockwave is produced by ablation of the surface by the pulse. That is, the light penetrates material to a depth where the electronic density corresponds to the critical density for the wavelength of light. The light energy heats the material it penetrates into the keV temperature range. This results in a plasma cloud which blows away from the surface into free space. To conserve momentum a strong shockwave then propagates into the material. The pressure produced depends on the power in the pulse and the irradiated spot size. The Janus laser produces about 2×10^{11} watt in each beam of a two-beam system. Focused on to a 0.3 mm diameter spot, this pulse will produce about 2 TPa (20 Mb) in aluminum. The shock pressure produced is a weak function of material density.

Experiments are presently being performed to demonstrate the feasibility of using high-power lasers to make material property measurements at ultrahigh pressures; i.e., above 1 TPa (10 Mbar).⁶ The measurement of shock velocity has been performed using distance intervals of $10 \mu\text{m}$ and time intervals of 400 ps. The purpose of this work is to obtain equation of state data.

High power lasers are capable of achieving very high temperatures in both compression and expansion from normal density. Diagnostic techniques are being developed to study these plasmas⁷ but much work remains to be done.

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Figure 1

Schematic representation of optical diagnostics used with isobaric expansion experiment. When the sample is heated it expands, as indicated in the streak record. An overall shadowgraph is also taken to insure that the slit is viewing a representative portion of the sample (after Gathers et al).

Figure 2

Thermal expansion of liquid lead (after Hodgson)

Figure 3

Electrical resistivity of liquid lead (after Hodgson)

Fig. 4. Schematic of the operation of the two-stage gun. (a) The hot gases from the gunpowder detonation drive a piston that compresses hydrogen gas in the pump tube. (b) The high-pressure hydrogen gas breaks the rupture valve and accelerates the projectile.

Figure 4

Figure 5

Shock Hugoniot of Liquid Argon