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SOUND VELOCITIES IN SHOCKED LIQUID DEUTERIUM

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Recent measurements of shock temperatures and laser-driven Hugoniot measurements of shocked liquid deuterium strongly indicate that molecular dissociation is important above 20 GPa. Since the effect of dissociation is small on the Hugoniot pressure up to the 30 GPa limit of conventional impact experiments, other methods must be used to test our understanding of the physics of highly compressed deuterium in this regime. We have recently performed experiments to measure the sound velocity of deuterium which test the isentropic compressibility, a derivative quantity. We used the shock overtake method to measure the shock velocity at 28 GPa. These preliminary data provide support for a recently developed molecular dissociation model.

INTRODUCTION

During the past several years, the properties of shocked liquid deuterium and hydrogen have been the subject of many new experimental studies. The equation of state (EOS) along the principal Hugoniot was determined by Nellis, *et al.* (1), and theoretical models were developed subsequently. (2,3) Recently, new shock temperature measurements led to the development of a new model, in which the effective molecular dissociation energy decreases with decreasing volume. (4) Extrapolation of those results to pressures above 100 GPa indicated that deuterium would be substantially more compressible in this pressure region than previously thought. More recently, laser-driven experiments were performed to test that prediction, (5) and those results support the predictions of the model in large part. However, the uncertainties in the latter experiments are large. In other experiments, Weir, *et al.* (6) found evidence for the formation of metallic hydrogen at higher densities and lower temperatures, using quasi-isentropic compression of the liquid.

Measurements of the EOS of the fluid in the pressure range of the most accurate experimental methods (impacts) generally will not provide convincing evidence of small amounts of molecular dissociation, since their effect on the EOS below 30 GPa is small. This suggests the measurement of derivative quantities such

as sound velocity or the Grüneisen parameter, both of which should be sensitive to the rate of change of compressibility. The sound velocity c of a rarefaction wave is given by

$$c^2 = - \left(\frac{\partial P}{\partial \rho} \right)_S \quad (1)$$

where P is pressure, ρ density, and the derivative is at constant entropy S . The sound velocity is also related to the Grüneisen parameter through the expression (7)

$$c = V \left[\left(\frac{\partial P}{\partial V} \right)_H \left[(V_0 - V) \frac{\gamma}{2V} - 1 \right] + P \frac{\gamma}{2V} \right]^{1/2} \quad (2)$$

where the Grüneisen parameter given by

$$\gamma = V \left(\frac{\partial P}{\partial E} \right)_V \quad (3)$$

can be obtained from shock Hugoniot experiments. Measurements of the sound velocity using the overtake method (8) can provide high accuracy, and an unambiguous test of our understanding of dense, hot, fluid deuterium.

EXPERIMENTAL

The shock overtake method exploits the fact that the sound velocity behind a shock is greater than the shock velocity, and thus will overtake it eventually. A target is impacted with a thin impactor; when the impact-generated shock reaches the back surface of the impactor, the pressure drops and a rarefaction wave moves at the sound velocity into the target. If the sound velocities in all layers at high pressure are known, then the time when the overtaking rarefaction reaches the shock provides a direct measure of the sound velocity. For shocked fluids at high temperatures such as deuterium, the intensity of the emitted light varies very strongly with shock velocity or pressure. Thus, observation of the light intensity emitted by the shock front provides a sensitive way of determining the overtake time.

FIGURE 1. Schematic of the optical arrangement for sound velocity experiments. The Ta impactor is embedded in a polycarbonate sabot (not shown), and impacts the Al baseplate, generating a strong shock. Light emitted by the shocked liquid D_2 sample is collected by a seven-fiber bundle which is placed near the Al_2O_3 window. Not shown are trigger pins and a Pt resistance thermometer placed inside the sample cavity.

FIGURE 2. Photomultiplier data showing time dependence of light emitted from shocked liquid deuterium at 506 and 700 nm, for the experiments described in the text at a pressure of 28 GPa. The regions of relatively constant signal ($0 < t < 260$ ns) indicate steady shock propagation in the D_2 sample. The overtaking rarefaction wave decreases the pressure and emitted intensity when it arrives at the shock front. To determine the arrival time, we made lineal fits to the data, and took the intersection as the arrival time. The sharp and brief intensity peak at about 420 ns is due to shock arrival at the Al_2O_3 window.

We used a two-stage light gas gun to accelerate a thin (0.5 mm) Ta projectile to 7.41 km/s in the experiment described here. The design of the cryogenic targets and sample preparation methods for hydrogen experiments were described elsewhere. (1) The projectile was incident on a 1.5 mm Al baseplate, and the D_2 sample was 6 mm thick, with an initial temperature of 20 K and density of 0.171 g/cm³. Light emitted from the shocked sample was collected by a 7-fiber bundle placed next to an Al_2O_3 window in contact with the sample. This system has been described previously (9,4) and is depicted schematically in Fig. 1. Measurement of the steady part of the signal provides a measure of temperature and emissivity of the shocked D_2 at the Hugoniot pressure of 28 GPa. Since the rise of the light emission occurs when the shock enters the sample (it becomes optically thick in < 1 ns), the overtake time can be located easily as shown in Fig. 2.

We used a graphical method to determine the overtake velocity, as depicted in Fig. 3. In the figure, the

FIGURE 3. Wave interactions and graphical solution for the overtake experiment in liquid D_2 . Bold lines indicate shock fronts, thin lines the position of material interfaces, and dashed lines the rarefaction waves. Note that the rarefaction which eventually overtakes the D_2 shock traverses a region of shocked and released Al

FIGURE 4. Comparison of two calculations of the sound velocity in shocked deuterium vs. shock pressure. The dashed line is calculated from Hugoniot data on liquid H_2 and D_2 , the dot-dash line and open circles from the model presented in Ref 4. The experimental point at 28 GPa and a compressed density of 0.6 g/cm³, with a sound velocity of 8.91 km/s is depicted by the solid circle. Since this datum is preliminary, the experimental uncertainty has yet to be determined, and no error bars are shown.

positions of the material interfaces are shown by thin solid lines, the shocks by bold lines, and the leading edge of the rarefaction waves are represented by dashed lines. The sound velocity in shocked Ta at the initial shock pressure of 189 GPa was found by Shaner, *et al.* (10), and we used unpublished measurements of the sound velocity in shocked Al at this pressure by Brown. (11) The experimental geometry we used is complicated by a backward rarefaction wave at the Al/D₂ interface. We used a simple Grüneisen model of the Al to calculate the sound velocity in Al initially shocked to 189 GPa and released to 27.6 GPa.

At the conditions of the experiment, the D₂ sample density and temperature are 0.653 g/cm³ and 5500 K, respectively. However, we note that these values are based on a modest extrapolation of the measured Hugoniot. The sound velocity was found to be 8.91 km/s. Since the sound velocity in the shocked and released Al is still somewhat uncertain, this value should be viewed as preliminary.

Now let us compare this datum with the predictions of the new model proposed earlier (4), and calculations based on previous experiments. The experiments reported by Nellis, *et al.* (1) in shocked H₂ and D₂ allow us to calculate an approximate Grüneisen parameter, since we can determine Eq. (3), and thus sound velocity (Eq. 2). These are plotted in Fig. 4, and show that the present data support the idea of enhanced dissociation of D₂ at moderate shock pressures. Clearly, more data are needed over a wider pressure range.

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