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Shock-Compression Experiments and Reflectivity Measurements in Deuterium up to 3.5 Mbar using the Nova Laser

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Abstract

We report on measurements of the equation of state and optical reflectivity at 1064 nm wavelength of a high pressure shock front propagating through a sample of liquid deuterium. We find that the shock front reflectivity increases from a low value (< 3.5%) to a saturation level of 65% in the pressure range of 0.22 - 0.55 Mbar. The pressure range where this metallization transformation takes place coincides with the pressure range where high compressibilities were observed on the principal Hugoniot.

1 Introduction

The metallic transition in hydrogen and its effects on the equation of state (EOS) at pressures near 1 Mbar are important for models of many astrophysical objects, including the Jovian planets [1] and low mass stars [2], as well as the design of deuterium-tritium-burning targets for inertial confinement fusion [3]. Fig. 1 shows the phase space of hydrogen in the vicinity of the finite-temperature insulator-metal transition. This regime of high density and extreme pressure is very difficult to approach theoretically since it is a strongly correlated, partially degenerate composite of molecules, atoms, and electrons. This makes reliable experimental data essential as a guide to theory, but meaningful measurements on the Hugoniot in this regime have until recently been unattainable. Using a high power laser, we have accessed this regime by shocking liquid D_2 to pressures at and above the metallic transition where we measured the thermodynamic properties of the shocked state. Here, we describe measurements of the compressibility and optical reflectivity of shocked liquid deuterium from 0.22 to 3.4 Mbar. The experiments were performed on the Nova laser [4]. They show that there is a regime of high compressibility observed above 0.25 Mbar on the Hugoniot coinciding with a transformation from molecular fluid to liquid metal. We find a metallic transformation in the 0.2-0.55 Mbar pressure range, a factor of ten lower than the highest static (room temperature) pressures so far reached, and a factor of three lower than the metallization pressure observed by Weir et al.[5].

2 Experiments

The experimental arrangement for measuring laser-driven shock waves in liquid deuterium has been described previously [6]. Using one beam of the Nova laser we generate a high pressure shock wave in a pusher material (either Al or Be). Behind the pusher is a volume filled with liquid deuterium sample at density 0.17 g cm^{-3} and temperature 20 K. After the shock emerges from the pusher rear surface, the pusher-deuterium interface moves at constant velocity behind the shock front in the deuterium. A second beam of Nova generates an x-ray source that allows us to radiograph the positions of the shock front and the pusher-deuterium interface as a function of time, obtaining both shock speed and particle speed.

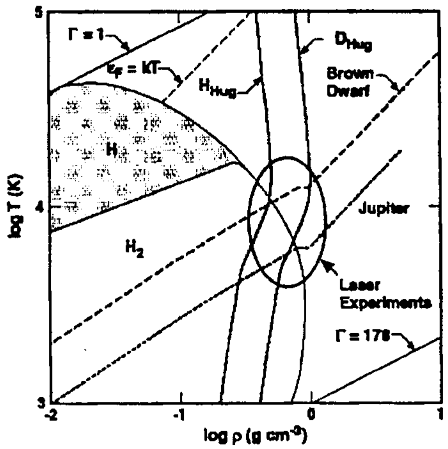

Figure 1: Model phase diagram of hydrogen in the regime of the fluid metal-insulator phase transition.

From this information we determine the pressure and density in the shock compressed fluid using the Rankine-Hugoniot relations [6].

Compression data are shown in Fig. 2. At the lowest compression, the laser data agree with gas gun results [7]. The most striking feature is the pronounced compressibility observed above 0.25 Mbar, about 50% higher than that predicted by the SESAME EOS [8]. The data more closely follow the models of Saumon-Chabrier [9] and Ross [10]. These models use minimization of the free energy of a mixture of molecular, atomic, and ionic species to determine species concentrations and establish thermodynamics of the mixture. Monte Carlo simulations [11] show a high compression but at a low pressure. The ACTEX model [12] also predicts a high shock density. However, the paths to higher pressure of these latter models lie to the low-density side of the data. A tight binding molecular dynamics Hugoniot [13], like SESAME, predicts only slight effects of dissociation and ionization. The shock front was also observed face-on using a 15 ns FWHM laser pulse from a laser operating at 1064 nm in a velocity interferometer (VISAR) configuration [14]. Noting that the shock front is reflecting, with this method we obtained accurate ($\sim 1-2\%$) time- and space-resolved measurement of the shock front velocity.

The reflectivity of the shock is also determined in these measurements, where each experiment provides one value of shock reflectivity as a function of shock speed, which, via the measured Hugoniot, can be mapped to pressure. Shown in Fig. 3 are results obtained a series of such measurements with Hugoniot pressures ranging from 0.55 Mbar to 3.4 Mbar. Two additional experiments specially designed to produce a decaying shocks in the deuterium were used to produce the continuous, lower pressure measurement in the figure. At the lowest observable shock pressure we found a reflectivity of approximately 3.5%, increasing to an asymptotic level of approximately 60 to 65%. This value is comparable to that of a liquid metal. The metallization coincides with the high compressibility observed on the principal Hugoniot, suggesting a connection between the high compressibility and the transformation of the molecular liquid into a liquid metal phase. Such a connection is explicitly assumed in the model of Ross [10] that describes a continuous dissociation of the molecular fluid directly into the monatomic metallic phase. The calculation of Saumon and Chabrier [9] predicts a similar transformation.

In these data we find no evidence of discontinuous behavior in the reflectivity as a function of shock velocity, such as might be expected if metallization occurs through a first

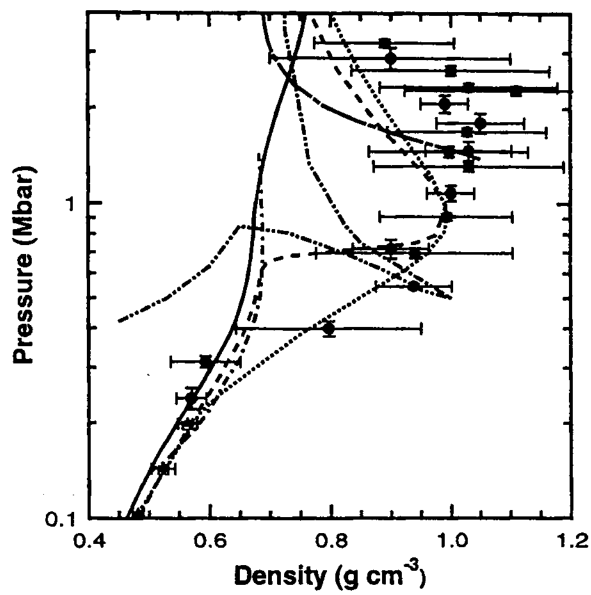

Figure 2: Laser Hugoniot data. Triangles are gas gun data [7]. EOS models are Ross (dots) [10], SESAME (solid) [8], Saumon and Chabrier (dash) [9], ACTEX (dash-long-dash) [12], Monte Carlo simulations (chain double dot) [11], and tight binding molecular dynamics simulations (dot dash) [13].

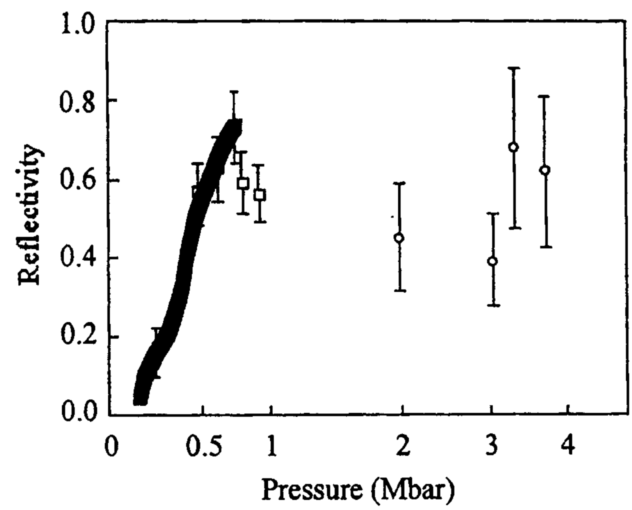

Figure 3: Reflectivity at 1064 nm of the shock front in liquid deuterium. Squares are from Al pushers; circles, Be pushers. The curve is from decaying shocks. Error bars reflect uncertainty in the reference levels. The Be pusher surfaces were rougher than the Al surfaces.

order phase transition. However, this does not rule out the existence of a first order transition since the principal Hugoniot may not pass through the coexistence region, but near the critical point where the thermodynamic parameters vary continuously. Further experiments at other optical probe wavelengths on and off the principal Hugoniot will provide more information on this high pressure-high temperature transformation in deuterium.

Acknowledgements

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References

[1] Smoluchowski, R., Nature, 215 (1967) 691.

[2] Saumon, D., Hubbard, W. B., Chabrier, G., and Van Horn, H. M., Astrophys. J. 391 (1992) 827.

[3] Lindl, J., Phys. Plasmas, 2 (1995) 3933.

[4] Campbell, E. M., Laser Part. Beams, 9 (1991) 209.

[5] Weir, S. T., Mitchell, A. C., and Nellis, W. J., Phys. Rev. Lett. 76 (1996) 1860.

[6] Da Silva, L. B., et al., Phys. Rev. Lett. 78 (1997) 483; Collins, G. W., et al., Science 281 (1998) 1178.

[7] Nellis, W. J., et al., J. Chem. Phys. 79 (1983) 1480; Holmes, N. C., Ross, M., and Nellis, W. J., Phys. Rev. B 52 (1995) 15835.

[8] Kerley, G., J. Chem. Phys. 73 (1980) 460.

[9] Saumon, D. and Chabrier, G., Phys. Rev A 44 (1991) 5122; 46 (1992) 2084.

[10] Ross, M., Phys. Rev. B 58 (1998) 669.

[11] Magro, W. R., Ceperley, D. M., Pierleoni, C., and Bernu, B., Phys. Rev. Lett. 76 (1996) 1240.

[12] F. J. Rogers, F. J., Astrophys. J. 310 (1986) 723.

[13] Lenosky, T. J., Kress, J. D. and Collins, L. A., Phys. Rev. B, 56 (1997) 5164.

[14] Celliers, P. M., et al., Appl. Phys. Lett 73, (1998) 1320.

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