Quartz standard at high energy laser facility for water up to five Mbar with the help of shock Hugoniot data

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Abstract

In this work, we present experimental results on the behavior of liquid water at megabar pressure. The experiment was performed using the HIPER (High-Intensity Plasma Experimental Research) laser facility, a uniaxial irradiation chamber of GEKKO XII (GXII) at the Institute of Laser Engineering (ILE), and the PHELIX at GSI (GSI Helmholtz Centre for Heavy Ion Research), a single-beam high-power laser facility, to launch a planar shock into solid multilayered water samples. Equation-of-state data of water are obtained in the pressure range 0.50–4.6 Mbar by tuning the laser-drive parameters. The Hugoniot parameters (pressure, density, etc.) and the shock temperature were simultaneously determined by using VISAR and SOP as diagnostic tools and quartz as the standard material for impedance mismatch experiments. Finally, our experimental results are compared with hydrodynamic simulations tested with different equations of state, showing good compatibility with tabulated SESAME tables for water.

Introduction

Equation of state (EOS) of matter at extreme thermodynamic states is of relevance for several fields in physics, especially in laboratory astrophysics and in inertial confinement fusion (ICF), where precise knowledge of the EOS is required. Water is predicted to be abundant in the outer planets of the Solar System, as well as in many of the recently discovered exoplanets. In particular, it is one of the principal ingredients of the mantles of giant planets such as Uranus, Neptune, and Jupiter [1]. The observation of large and asymmetric magnetic fields in these planets [2–4] indicated that the mantle is the origin of the field. As the dynamo theory requires the presence of a conductive material, it was suggested that one or all of the main ingredients of the mantle (ammonia, water, and methane, i.e., carbon [5, 6]) experience a phase transition to a conducting state. Pioneering theoretical work has been done calculating the properties of the superionic phase of water at planetary conditions [7–9]. Therefore, water at very high pressures has been extensively studied in recent works [8, 10–14]. Recently [15, 16], the superionic phase of water was detected experimentally along the Uranus and Neptune isentropes at about 1.5 Mbar by laser shocking water samples precompressed up to 28 kbar. The new superionic phase is predicted to span the pressure range of 1.5 to 6 Mbars.

Superionic water is a solid system that has high ionic conductivity well below the melting temperature. Whether H2O in planetary interiors is in the superionic or metallic state is of great importance for understanding the source of the planetary magnetic field.

Laser-driven shock compression is a useful technique for generating high pressure and temperature conditions similar to the inner part of Neptune and Uranus. However, measuring $P - \rho - T$ simultaneously is challenging, particularly temperature, as this requires absolute intensity measurements which are not necessary for the determination of the pressure or the density. In this work, we conducted laser-driven shock experiments on

H2O samples up to 4.6 Mbar; along with pressure and density, we evaluated the temperature from measured reflectivity and thermal emission of the shocked sample.

The impedance mismatch (IM) method is widely used for the determination of Hugoniot of sample material. Given that one knows Hugoniot of a “standard” material that is used as a reference, the Rankine–Hugoniot (RH) [17] set of equations, expressing the conservation laws, can be used to relate the experimentally measured shock velocity (D_s) in the standard material before the shock reaches the standard-sample interface in the sample after it passes through the interface. In this work, we used *z*-cut -quartz (SiO_2) as a reference material [18, 19] which, at ambient pressure, is transparent to visible light and becomes reflective at pressures above 1 Mbar [20]. As diagnostic tools, we used the velocity interferometer system for any reflector (VISAR) [21–25] which allowed us to make a precise measurement of shock wave parameters and characterize the EOS of water. The RH set provides information of P and ρ , but not of *T*, whereas *T* is also an important thermodynamic parameter. Indeed, in this work, we also measured the temperature using streaked optical pyrometry (SOP) diagnostic data.

GEKKO XII-ILE Laser Facility

The first experiment was carried out on the HIPER (High-Intensity Plasma Experimental Research) laser facility, a uniaxial irradiation chamber of the GEKKO XII (GXII) laser at the Institute of Laser Engineering (ILE), Osaka University. Up to 12 beams of neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, frequency tripled (351 nm), were used in the experiment. The laser pulse temporal profile was approximately square shape in time with full width at half maximum (FWHM) 2.5 ns with typical rise and fall time of 100 ps each. The focal spot diameter was 600 μm flat top. SSD (smoothing by spectral dispersion technique) was applied to smooth out the beams. Kinoform phase plates were also used to achieve uniform irradiation, resulting in good shock front planarity.

Figure 1 shows the experimental setup and target configuration. A typical target assembly consisting of 10 μm parylene (C8H8) will be referred to as CH/200 nm Au/100 μm quartz (with AR@1054&532 both sides) nominally, ~500 μm water/100 μm quartz (with AR@1054&532 both sides). The laser initially hits the 0.1 μm-thick Al layer, coated over the CH layer, to avoid laser shine through. The CH layer is the actual ablator, and quartz is the pusher layer. The 200 nm gold layer was placed to stop any X-rays from the plasma corona and avoid preheating of water. Water cells were produced at the Technical University of Darmstadt (Germany) target fabrication department. Due to the low *Z* ablator and the low laser intensity, X-ray radiation is low and characterized by low photon energy. The Au layer is capable to stop the X-ray radiation; thus, preheating of water is negligible.

The primary diagnostics were the VISAR and SOP. Two line-imaging interferometers (VISARs) allow to record time-resolved Doppler shift of the velocity of the fast-moving reflector and also the optical properties such as reflectivity [21–26]. These VISARs had different velocity-per-fringe (VPF) sensitivities to resolve the -phase jump ambiguities due to the shock velocity jump at material interfaces. The sensitivity of the two VISARs was 7.523 km/s and 4.476 km/s taking into account the refractive index of SiO_2. The VISAR probe beam was an injection-seeded *Q*-switched YAG laser. The pulse duration of the probe was ~10 ns at the FWHM, and its wavelength was 532 nm. The postprocessing of the VISAR raw data obtained in the experiment allows determining [27] the fringe position to

10% of a fringe, while the multiple fringe shifts allow the precision of the shock velocity measurements to be a few percent. Our VISAR analysis showed uncertainties in measured D_s of the order of 3%.

To measure the shock temperature, we used SOP [28–30]. The self-emission of the shocked sample at wavelength 450 nm with 38 nm bandwidth was recorded spatially and temporally resolved, using an absolutely calibrated SOP.

PHELIX-GSI Laser Facility

The second experiment was conducted at the GSI facility using the PHELIX laser, a flash-lamp-pumped Nd:glass laser utilizing the second harmonic at wavelength 527 nm. The spatial profile was flat top with spot 350 μm FWHM obtained by an appropriate phase plate [31], and the temporal profile was top hat with a duration of 3.5 ns (FWHM). The laser was focused onto a multilayered target with intensity I 5.49 × 10^{12} W/cm^2 to 2.52 × 10^{13} W/cm^2. The ablation pressure was approximately 12 Mbar, was generated in our plastic ablator parylene with gross chemical formula (C8H8), and was estimated from the well-known scaling laws [32–34] for given intensities.

$$P = 8.6\ (\ I\ /\ 8.6\ (\frac{I}{10^{14}})^{2^{-3}}\ )\ \ \lambda^{2^{-3}} (\frac{A}{2Z})^{\frac{1}{3}}$$

where A and Z are the atomic mass number and the atomic number of the target material: I is in W/cm2, P is in Mbar, and λ in µm. Targets were also produced at the Technical University of Darmstadt (Germany) target fabrication department.

The target configuration and the experimental setup are presented in Figure 2. The sample consists of 15 μm C8H8 (parylene)/5 μm epoxy/10 μm Al/7 μm epoxy/100 μm quartz (with AR@1054&527 both sides) nominally, ∼500 μm water/100 μm quartz (with AR@1054&527 both sides). The laser initially hits the 0.1 μm-thick Al layer, coated over the CH layer, to avoid direct laser shine through. Epoxy was used to glue CH/Al and Al/quartz interfaces. The CH layer is the actual ablation layer, and quartz is the pusher layer. The 10 μm Al layer was placed to stop any X-rays from the plasma corona and avoid preheating of the quartz/water layers. The VISAR laser had a wavelength of 660 nm, and the associated sensitivities were 1.285 km/s/f and 4.7 km/s/f, respectively. Also, SOP was looking at the self-emission of the shocked target; however, here, we report only VISAR results and compare with findings on water samples from the GEKKO XII laser facility.

The impedance matching method

The impedance-matching method [5, 17–19, 35] was used to estimate the shock state in water after passing the quartz/water interface; an illustrative method is shown in Figure 3. Because of the impedance mismatch at the SiO_2/H_2O interface, the shock wave produced a transmitted shock into H_2O and a reflected rarefaction wave propagating back into quartz. In the rarefaction wave, the shock-compressed quartz undergoes isentropic release until its pressure and particle velocity match those of shocked water. The IM method requires precise knowledge of Hugoniot and release behavior of the standard reference material (quartz in our case) and the Rankine–Hugoniot (RH) jump relations, which are derived from the conservation laws, mass, momentum, and energy to close the system and derive all the remaining thermodynamic parameters: where $\rho, D_s, U_p, P\ and\ \varepsilon$ denote the density, shock velocity, particle velocity, pressure, and internal energy behind the shock. The initial states are denoted with subscript 0. The third equation plotted in the (P-U) plane gives the so-called Rayleigh line of the material. Figure 3 illustrates such a method, deriving the shock pressure in water and the particle velocity.

$$\frac{\rho}{\rho_0} = \frac{D_s}{D_{s-}U_p}$$

$$P - P_0 = \rho_0 D_s U_p$$

$$\varepsilon - \varepsilon_0 = \frac{1}{2}(P + P_0)\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right)$$

Hydro Simulations:

1D radiative hydrodynamic simulations were performed with MULTI-1D [36] to comprehend our experimental results. The laser temporal profile of the pulse was flat top in time with a plateau duration of 2.5 ns at FWHM and rise and fall times of 0.1 ns. In the simulation, we utilized the SESAME tables of the following materials which consist of our target SESAME table 7770 for parylene [37], SESAME table 2700 for gold [37], SESAME 7385 for quartz [37], and SESAME tables 7150, 7153, and 7154 for water [37]. Concerning the water EOS, we compared different models of EOS tables coming from the SESAME database [37], from QEOS [38], and from FEOS [46], in all cases setting the initial density at $\rho_0 = 0.98(g/cm^3)$ in order to check the validity of the EOS data. The use of 1D simulation to interpret the experimental results is confirmed because of the use of appropriate phase plate resulting in a large focal spot (~600 μm). In addition to this, the justification of the 1D approximation is supported by two experimental observations.

Raw data from VISAR images (see Figure 4) indicate that the shock breakout is quite flat both at metal/SiO_2 and at SiO_2/H_2O interfaces. At this point, we must note that 2D effects will result in curvature, initially affecting the edges of the shock front, yet gradually advancing to the center. However, in our experimental results, the curvature of the shock front is not observed suggesting that the 2D effects in hydrodynamics can be neglected. In our case, the velocity of the shock is maintained and decaying quite slowly, and actually (within error bars), the decay obtained by analysing the VISAR images is compatible with the results of 1D simulations. The reduction of shock pressure and velocity during propagation is caused by two phenomena: (a) the release wave from the target front side catching up the traveling shock and (b) 2D effects in shock front propagation. In fact, due to the fair agreement of conducted experiment with 1D simulations, we conclude that (b) is not important. Indeed, a much faster decay of shock pressure and velocity would be expected if 2D effects were important.

Conclusion

In summary, we obtained EOS data of water along the principal Hugoniot up to 5 Mbar. Water samples, contained within a multilayered water cell, were dynamically compressed in planar geometry using the high-power laser facilities GEKKO XII (ILE) and PHELIX (GSI). Utilizing quartz as a standard material in both experimental campaigns and the main diagnostics such as VISAR/SOP substantially reduced experimental errors in optimized experimental conditions. The impedance mismatching analysis allowed to verify that $P, \rho, (\varepsilon - \varepsilon_0)$, and the Hugoniot data are in fair agreement with those predicted by SESAME table 7150, and on the contrary, they show a significant difference concerning the Hugoniot curve calculated using DFT-MD simulations. Also, our experimental outcome showed good agreement with simulations performed with the radiative hydro code MULTI-1D using the SESAME tabulated EOS, the QEOS model, and the FEOS model, a modified version of the QEOS. The agreement with 1D simulations shows indeed that, in our experimental setup, 2D effects in hydrodynamics are negligible, a result which mainly depends on the use of laser focal spots. For a few shots, we could also measure the temperature of shocked material using calibrated SOP diagnostics. Our data confirm previous experimental results and show that, in the pressure range up to 4.6 Mbar, water is in a reflective state.

Author:

Mr. Mallesh Bingi is currently working as an Associate Professor in the department of Humanities and Sciences at Guru Nanak Institute of Technology. He has twelve years of professional teaching experience in Physics. A phenomenal professor who has devoted and dedicated his time for the betterment of his students. He always strives for the better life of his students and for that reason he has been imparting immense knowledge with humongous enthusiasm.