

Shock compression of liquid helium to 360 GPa

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Data for the shock equation of state of helium are obtained up to 360 GPa, nearly doubling the pressure of previous experimental measurements. The helium samples are first precompressed to $0.35\text{--}0.42\text{ g cm}^{-3}$ in a diamond anvil cell prior to laser-driven shock compression at the Omega Laser Facility. Time-resolved Doppler velocimetry and pyrometry reveal significant reflectivity and greater compressibility compared to the predictions of existing broad-range tabular equation of state models, which may be caused by the onset of ionization. These experimental observations, however, are largely captured with molecular-dynamics simulations based on density functional theory, affirming the ability of first-principles techniques to capture complex physics, while enabling critical insight for the behavior of warm dense helium in Jovian interiors and white dwarf atmospheres.

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I. INTRODUCTION

Helium is the second most abundant chemical element, and characterizing its behavior in high-pressure environments is essential for understanding Jovian interiors and white dwarf atmospheres [1–7]. In particular, the metallization of helium and its miscibility with hydrogen at megabar-level pressures may have dramatic consequences on the convective barrier predicted to exist within Jupiter, separating helium-depleted and helium-rich layers [3,8–11]. Competing models predict considerably different band-gap closures at $\sim 2\text{ g cm}^{-3}$ [12] and $\sim 10\text{ g cm}^{-3}$ [13], with the latter suggesting that only insulating helium exists within Jupiter, motivating the need for additional experimental data. Mankovich & Fortney furthermore predicted the accumulation of a helium-rich layer above the rocky core of Saturn, resulting from hydrogen-helium phase separation [14]. This process is not yet understood, as the diverging predictions between experiments and *ab initio* simulations illustrate [11,15]. Moreover, understanding high-pressure helium is essential for modeling heat transfer in the helium-rich atmospheres of white dwarfs [16], enabling constraints on models of interior structure and thermal evolution

that are highly sensitive to ionization (metallization) behavior [17–20].

Beyond these applications, the simplicity of the helium atom makes it an important benchmark for *ab initio* simulations, including density functional theory (DFT), molecular dynamics (MD), and path integral Monte Carlo (PIMC) calculations, especially at the megabar-level pressures of the notoriously challenging warm dense matter regime [21]. In particular, its monoatomic nature makes helium the simplest element for which pressure- or temperature-induced ionization can be isolated from molecular dissociation [22–32]. While past studies have shown evidence for ionization, the parameter space over which helium ionizes is largely unexplored experimentally [33–35]. Further obfuscating our understanding are discrepancies in the pressure response predicted from existing models [36–40] beyond approximately 100 GPa for shocked helium initially precompressed near 1 GPa, a regime where data are limited to only six past experiments with initial pressures spanning 0.5–1.5 GPa, with no available data from 0.52 to 1.11 GPa [12,41]. Even after reanalysis of these experiments with improved quartz standard models [42], discrepancies with existing models [36–38], including the first-principles equation of state (FPEOS) [39], remain and motivate the need for experimental data to elucidate the behavior of helium and discriminate between existing models.

Experimental studies utilized diamond anvil cells (DAC) to statically compress helium up to 58 GPa at room temperature and examined the pressure dependence of the refractive index and melting line [43–46], while experiments using gas-gun facilities to dynamically compress helium with shock waves documented the pressure-density shock equation of

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state (EOS) up to 56 GPa with high precision [47]. Achievable projectile velocities in such experiments [48], however, limit the maximum pressures. In addition, thermodynamic states are constrained to the material shock Hugoniot, limiting the attainable density when starting from cryogenic liquid near 100 kPa. Combining static and dynamic techniques, where a DAC achieves tailored precompression followed by laser-driven shock compression [49], enables access to conditions relevant to planetary interiors and white dwarf atmospheres [12,41,42].

This work presents data from four experiments at the Omega Laser Facility compressing helium in a DAC from initial static pressures of 0.76–1.20 GPa to shock pressures of 270–360 GPa, thereby extending experimental measurements to a regime where predictions from existing EOS models diverge [36–40]. These record pressures were achieved by designing the DAC such that the desired precompressed state could be reached with a thin diamond window (200 μm), efficiently coupling the pressure from the kilojoule-class laser drive to the sample [50]. The data show increases in reflectivity consistent with continuous ionization, which is also evident in the increased compression, and the pressure and temperature response is reasonably captured by FPEOS, resolving past discrepancies [12,41,42]. The present experimental study, therefore, provides additional confidence in the fidelity of first-principles methods to model the key thermodynamic and optical properties of helium at the extreme pressure and temperature conditions expected to exist in the deep interior of gas giant planets and in the atmospheres of white dwarf stars.

II. METHODS

The DAC is similar to those employed in Refs. [11,49,51] and is detailed in Fig. 1(a). In each experiment, supercritical fluid helium is compressed in a DAC with a back sapphire window at room temperature using a gas loading system and a ruby for initial pressure characterization [42,49,52]. The portion of the cell compressed to 0.76–1.2 GPa consists of layers of diamond (200 μm), quartz (15–17 μm), helium (100–180 μm), and sapphire (5000 μm). Adjacent to the quartz impedance standard are ruby spheres 5–10 μm in diameter used for pressure characterization [52]. The laser-irradiated side of the target (i.e., the diamond side) is coated with 3–7 μm of gold between the diamond and the 40 μm plastic ablator to shield the sample from x-ray preheat. The diamond is fixed in place by a tungsten-carbide seat, while a stainless steel gasket defines the pressure chamber.

In order of increasing precompression, the experiments are referred to as S74727, S70906, S74722, and S72497 throughout this work, with initial conditions in the compressed anvil cell summarized in Table I. The initial pressure, p_0 , was determined using the luminescence spectra of the ruby pressure gauges to within 0.03 GPa [52]. The initial temperature, T_0 , was determined with negligible error compared to that of the pressure. The initial density of the quartz standard, $\rho_{0,q}$, and the corresponding uncertainty were determined using coefficients from Ref. [53] and the Murnaghan EOS, and the refractive index $n_{0,q}$ and corresponding uncertainty were characterized according to Ref. [54] for the probe wavelength

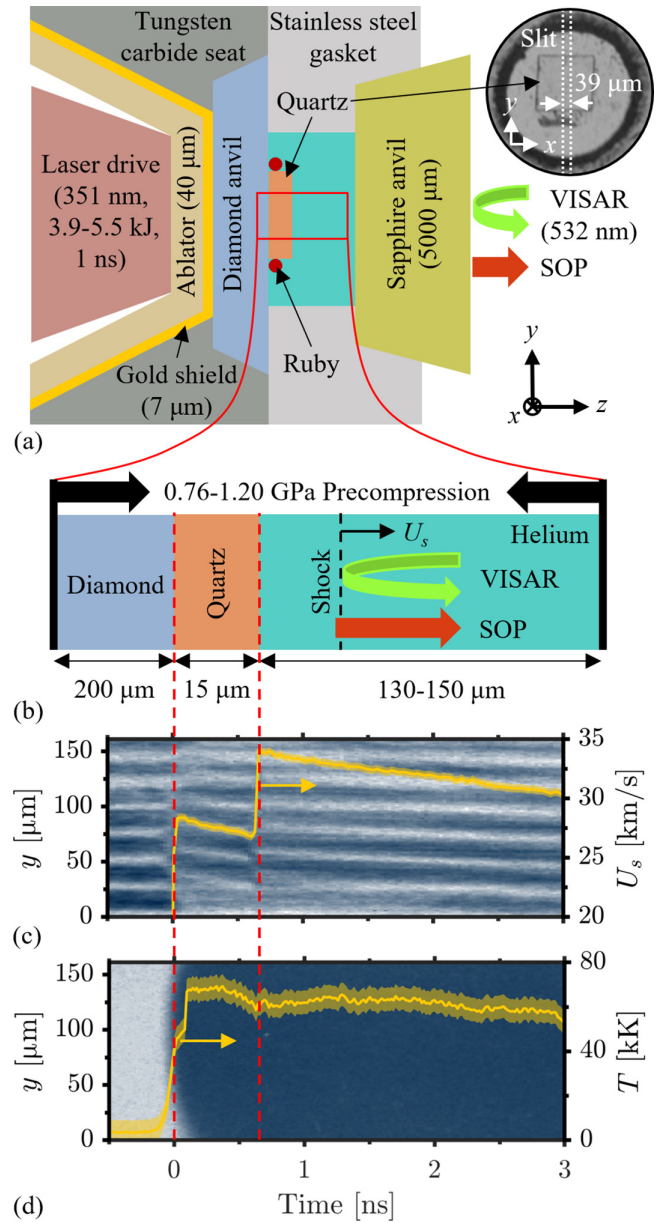


FIG. 1. (a) Schematic showing the DAC, including a micrograph (right) of the pressure chamber showing the quartz reference plate and the projection of the streak camera entrance slit onto the target (white dashed lines) for S74722. (b) Close-up of the schematic in panel (a) detailing the sample geometry, precompression, and shock transit. (c) Velocity interferometer for any reflector (VISAR) data vs time with overlaid shock velocity (yellow line) from S74722. The transition of the shock between materials is identified by the discontinuous jump. (d) Streaked optical pyrometry (SOP) data vs time with overlaid temperature (yellow line) from S74722. In panels (c) and (d), the shaded yellow region indicates measurement error.

of 532 nm [42]. The initial density of the helium, $\rho_{0,\text{He}}$, and the corresponding uncertainty were determined according to Ref. [44], and the refractive index $n_{0,\text{He}}$ and corresponding uncertainty were characterized according to Ref. [55]. Ten or twelve lasers generate a 1 ns square pulse delivering 3.9–5.5 kJ of ultraviolet radiation at 351 nm to the plastic ablator,

TABLE I. The precompressed conditions for each of the experiments performed in this work. The uncertainty in the parentheses corresponds to the last-reported digit. For example, 0.76(3) is equivalent to 0.76 ± 0.03 .

Shot ID	74727	70906	74722	72497
p_0 (GPa)	0.76(3)	0.95(3)	0.98(3)	1.20(3)
T_0 (K)	298	296	298	296
$\rho_{0,q}$ (g cm ⁻³)	2.701(3)	2.713(3)	2.715(3)	2.729(3)
$n_{0,q}$	1.5544(4)	1.5562(4)	1.5565(4)	1.5586(5)
$\rho_{0,He}$ (g cm ⁻³)	0.351(6)	0.385(5)	0.390(5)	0.422(4)
$n_{0,He}$	1.070(1)	1.077(1)	1.078(1)	1.084(1)

driving a shock into the DAC, through the quartz standard, and into the helium sample, as shown schematically in Fig. 1(b).

The reflective, self-emitting shock is tracked using the line-imaging velocity interferometer for any reflector (VISAR) system [56,57], generating the data shown in Fig. 1(c). Shifts in the VISAR fringes are proportional to changes in the apparent shock velocity U_{ap} , which is related to the actual shock velocity, $U_s = U_{ap}/n_0$ [56,57]. The effect of precompression on the indices of refraction [54,55] is considered for an accurate measurement. Despite the use of antireflective coatings on the quartz impedance standard and sapphire window, the VISAR signal is influenced by reflections from stationary interfaces, the treatment of which is detailed in the Appendix.

As the shock passes from the quartz to the helium, it accelerates the interface to velocity u_p . The difference in shock impedance causes the transmitted shock to have a different velocity, resulting in a discontinuous shift in the VISAR fringes. The ambiguity in the absolute fringe shift is resolved using two VISAR channels with different sensitivities controlled by the etalon thicknesses ($16.0829 \text{ km s}^{-1}/6.9065 \text{ km s}^{-1}$ per fringe for the 3.096 mm/7.2095 mm etalon, respectively). Resolving the fringe discontinuity yields a set of possible solutions where the velocity traces from VISAR channels with different fringe sensitivities overlap. Matching the time-integrated shock velocity through the quartz layer to its known thickness resolves this ambiguity. The shock velocity in the quartz and the helium are then determined by fitting lines to both velocity histories leading up to and following shock breakout, respectively, and extrapolating to the breakout time. The final velocity is then determined as the average between the velocity for each history weighted by the inverse of the fringe sensitivity.

The error in the velocity measurements is taken to be the scaled L2 norm between the velocity histories from each VISAR measurement in both the quartz and helium according to

$$L_{2,m} = \left[\frac{1}{t_{b,m} - t_{a,m}} \int_{t_{a,m}}^{t_{b,m}} (U_{s,et1} - U_{s,et2})^2 dt \right]^{1/2}. \quad (1)$$

Equation (1) quantifies the typical amount by which the velocity histories from both VISAR measurements with different etalons, $U_{s,et1}$ and $U_{s,et2}$, differ over the time interval $t_{a,m}$ to $t_{b,m}$, where the subscript m refers to the material, quartz (q), or helium (He). Figure 2 shows the vacuum velocity histories

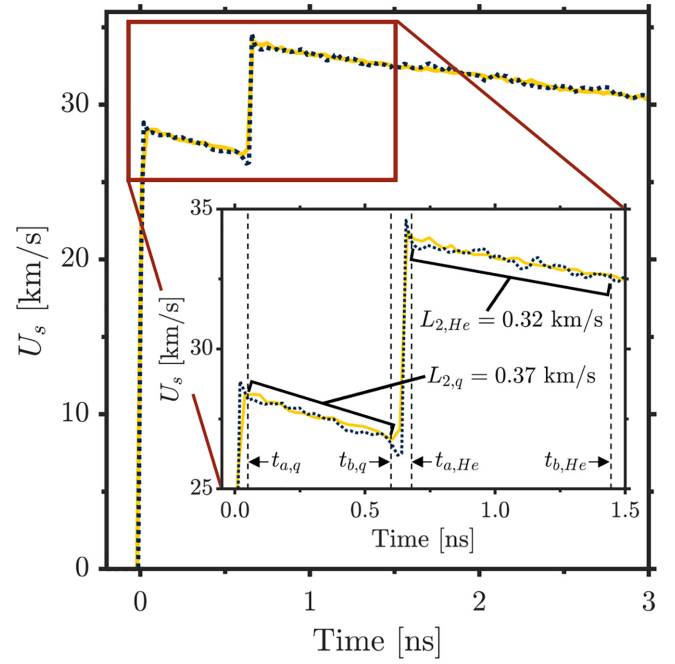


FIG. 2. The velocity histories for the 7.2095 mm etalon (solid yellow) and 3.096 mm etalon (dotted blue) for S74722. Vertical dashed lines in the inset indicate the bounds for the integral in Eq. (1) used to calculate the error shown.

from S74722 along with the L2 norm in both the quartz and helium calculated according to Eq. (1). Error from the refractive index (see Table I) is added in quadrature with the error in the apparent velocity and is given in Table II.

III. RESULTS

A. Shock velocity and impedance matching

Table II contains the energy E delivered to each experimental target along with the corresponding shock velocities. These data are compared to Refs. [12,41,42] in Fig. 3. We presently restrict our attention to shocked helium precompressed between 0.76 and 1.25 GPa to enable a detailed comparison between the data and predictions from existing models. In general, the data show good agreement with predictions from FPEOS, an EOS database that combines results from PIMC and DFT-MD simulations [39].

Because the particle velocity and pressure must be continuous at the interface between the shocked quartz and helium, the known shock response of the quartz standard can be used

TABLE II. The energy delivered to the target and the measured shock velocities for the present work. The uncertainty in the parentheses corresponds to the last-reported digits. For example, 28.04(30) is equivalent to 28.04 ± 0.30 .

Shot ID	74727	70906	74722	72497
E (J)	5460	3923	4986	4649
$U_{s,q}$ (km s ⁻¹)	28.04(30)	23.94(25)	26.62(37)	25.49(25)
$U_{s,He}$ (km s ⁻¹)	36.31(33)	30.89(34)	33.87(32)	32.14(32)

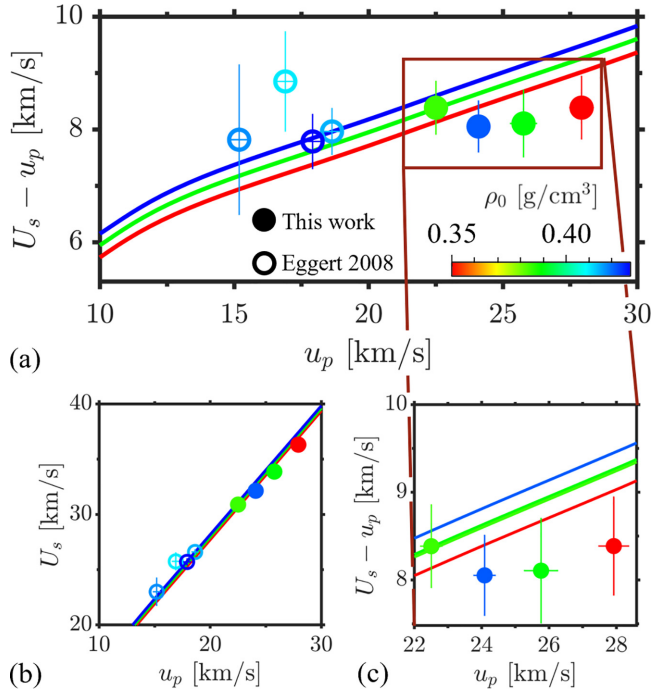


FIG. 3. (a) Difference between the shock and particle velocity vs particle velocity in helium for the present work (closed symbols) and past work [12,41] reanalyzed in Ref. [42] (open symbols). Color indicates the precompressed density. Three FPEOS Hugoniot curves [22,25,39] span the initial densities ($\rho_0 = 0.351, 0.389$, and 0.429 g cm^{-3}). (b) Shock velocity vs particle velocity. (c) Close-up of the data and corresponding Hugoniot curves.

to determine the state in the shocked helium using standard impedance matching techniques. We use a model for the shock Hugoniot in the precompressed quartz from Refs. [42,58] and the measured shock velocity to determine the state in the quartz downstream of the shock immediately prior to breakout. The intersection of the quartz isentrope from Ref. [59], representing the release wave emerging from the breakout interaction, passing through this state, and the equation from the Rankine-Hugoniot equations representing momentum conservation for the shock in helium, which requires the shock velocity in helium, gives the pressure and density in the helium. Error from measurements of the precompressed state in helium (density and pressure) and the shock velocities in both the quartz standard and the helium are propagated into the impedance matching calculation according to the Monte Carlo methodology detailed in Ref. [60].

The measured pressures and densities are reported in Table III and shown in Fig. 4, again alongside past data and

TABLE III. The density and pressure in helium. The uncertainty in the parentheses corresponds to the last-reported digits. For example, 1.515(97) is equivalent to 1.515 ± 0.097 .

Shot ID	74727	70906	74722	72497
$\rho \text{ (g cm}^{-3}\text{)}$	1.517(97)	1.418(75)	1.630(118)	1.684(92)
$p \text{ (GPa)}$	356.5(82)	268.6(59)	341.3(81)	327.9(53)

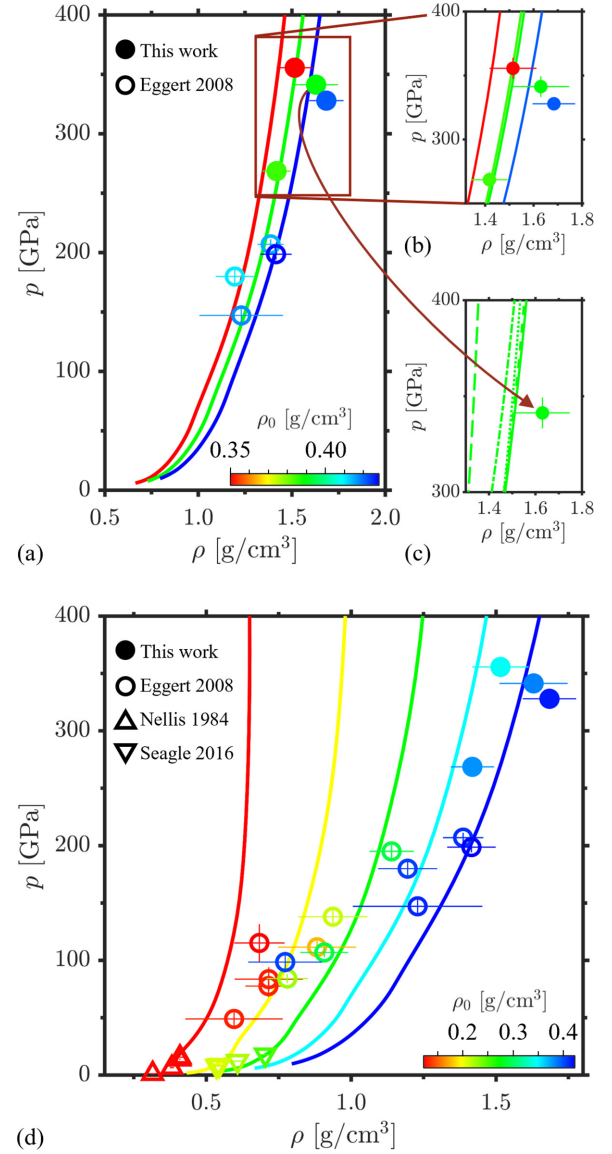


FIG. 4. (a) Pressure vs density in helium for the present work (closed symbols) and past work [12,41] reanalyzed in Ref. [42] (open symbols). Color indicates the precompressed density. Three FPEOS Hugoniot curves [39] span the initial densities ($\rho_0 = 0.351, 0.389$, and 0.429 g cm^{-3}). (b) Close-up of the data and corresponding Hugoniot curves. (c) S74722 with Hugoniot curves from LEOS20 (long dashed) [36], SESAME5764 (dash dotted), SESAME5761 (dotted) [37], REOS (short dashed) [38], and FPEOS (solid) [22,25,39]. (d) Same as panel (a), but covering a wider range of precompressed states with additional data from Refs. [12,41,42,47,62] (open symbols). Five FPEOS Hugoniot curves [39] span the initial densities ($\rho_0 = 0.122, 0.199, 0.275, 0.352$, and 0.429 g cm^{-3}).

predictions from FPEOS. The data indicate pressures near and in excess of 350 GPa and again show good agreement with FPEOS, as seen in Fig. 4(b). The three highest-pressure experiments show greater compression than the prediction of FPEOS, but still fall within, or very nearly within, the experimental error bars. Figure 4(c) also shows the predicted Hugoniot curves for S74722 from the tabular EOS models LEOS20 [36], SESAME5761 [37], and SESAME5764 [61].

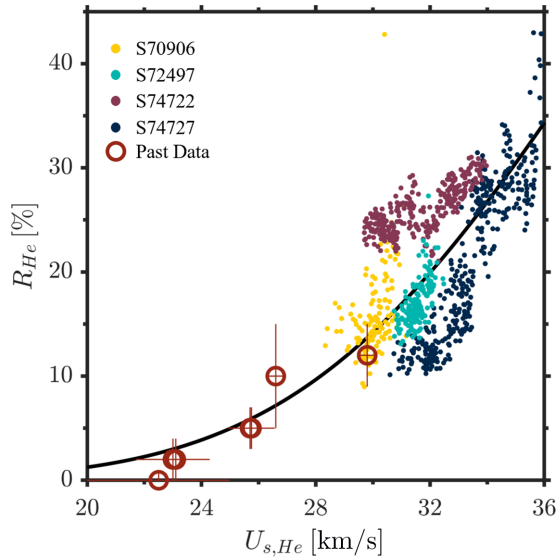


FIG. 5. Reflectivity vs shock velocity in helium for S70906 (yellow), S72497 (teal), S74722 (purple), S74727 (blue), and past work [12,41] reanalyzed in Ref. [42] (open symbols) with a combined Hill fit (black line).

These models combine a variety of physical assumptions to define the free energy over wide ranges of density and temperature that are adjusted to match selected experimental observations. The data are also compared to predictions from He-REOS.3 (helium Rostock EOS, herein referred to as just REOS), an EOS model derived from various approaches that are merged without the construction of a broad-range free energy [38]. Each of these models predicts a density less than what is measured for each experiment, sometimes by several times the experimental uncertainty. The predictions of these EOS models for S74727, S70906, and S72497 show similar trends. Of these models, SESAME5761, REOS, and FPEOS provide a reasonable agreement with experiments. Figure 4(d) contextualizes this agreement with respect to the broader range of available data [12,41,42,47,62]. The greater compressibility may be related to an increase in the internal molecular degrees of freedom due to the onset of ionization [22,24,25,39], which is further elucidated by reflectivity measurements discussed next.

B. Reflectivity, temperature, and conductivity

While the phase of the VISAR fringes enables velocity measurements, the amplitude encodes information enabling a measurement of the shock reflectivity at the laser wavelength of 532 nm, where the signal in quartz again acts as a measurement standard [63]. The reflectivity in helium, R_{He} , is determined by comparing the intensity of the VISAR signal in the quartz, $I_{V,q}$, and helium, $I_{V,\text{He}}$, where the reflectivity of the shock in the precompressed quartz standard is characterized as a function of its velocity, $R_q(U_{s,q})$ [42]. Specifically, the reflectivity in helium is given by $R_{\text{He}} = R_q(U_{s,q})I_{V,\text{He}}/I_{V,q}$. As in the quartz standard, the reflectivity in helium can be represented as a function of the shock velocity, $U_{s,\text{He}}$, as shown in Fig. 5. A four-parameter Hill equation, with the constraint that the reflectivity must be between 0% and 100%, is then fit

TABLE IV. The reflectivity and temperature in helium. The uncertainty in the parentheses corresponds to the last-reported digits, with the first entry representing the positive uncertainty and the second, the negative. For example, 77.5(90, 77) is equivalent to $77.5 + 9.0, -7.7$.

Shot ID	74727	70906	74722	72497
R_{He} [%]	35.5(68, 68)	16.6(49, 49)	26.3(85, 85)	20.4(33, 33)
T (kK)	77.5(90, 77)	46.8(36, 32)	58.0(76, 64)	54.7(33, 34)

to the combined data, which includes the reanalyzed past data [42], from which the reflectivity is extracted. The uncertainty in the reflectivity data is the sum of the error propagated from the velocity measurement (i.e., the difference between the reflectivity calculated with the nominal shock velocity and the reflectivity calculated with the nominal shock velocity plus or minus the reported uncertainty) and the standard deviation of the data from each experiment from the combined fit.

The reflectivity is reported in Table IV, represented by the symbol size in Fig. 6(a), and given as a function of temperature in Fig. 6(d), which also includes experimental data spanning a wider range of precompressed states [12,41,42] and DFT calculations from Refs. [28,64]. A four-parameter Hill equation, again with the constraint that the reflectivity must be between 0% and 100%, is fit to the combined experimental data set, as shown in Fig. 6(d). Although reflectivity is primarily a function of temperature, it also depends on density, with higher-density states at a given temperature generally exhibiting greater reflectivity and lower-density states exhibiting lower reflectivity. The reflectivity appears to increase continuously with increasing pressure and temperature, up to almost twice that measured in past experiments [12,41], but additional data are required to uncover the precise nature of the trend. The increase in reflectivity is, however, consistent with the onset of ionization.

The temperature in helium is determined by a comparison of the thermal emission of the shock front in quartz and helium measured by the streaked optical pyrometry (SOP) system, with example data shown in Fig. 1(d), where the slight increase in the signal intensity following shock breakout may be caused by space-time distortions and nonlinearity in the diagnostic sweep rate [65]. With the reflectivity now known, the temperature, T , is related to the spectral radiance, I_S , using a gray-body approximation as

$$T = T_C \{ \ln [(1 - R)A/I_S + 1] \}^{-1}, \quad (2)$$

where the calibration parameter T_C is a function of the system peak sensitivity ($T_C = 1.9$ eV for the present work) and A is a system calibration constant. Because the temperature in the helium is determined relative to the temperature in the quartz standard, the calibration parameter A drops out giving

$$T_{\text{He}} = T_C \{ \ln [(e^{T_C/T_q(U_{s,q})} - 1)I_{S,q}^*/I_{S,\text{He}}^* + 1] \}^{-1}, \quad (3)$$

where $I_S^* = I_{S,\text{ADU}}/(1 - R)$ and $I_{S,\text{ADU}}$ represents the analog-to-digital counts of the measured SOP signal. The temperature in the quartz standard as a function of the shock velocity, $T_q(U_{s,q})$, is therefore required to determine the temperature in the helium. While efforts are currently underway to extend the

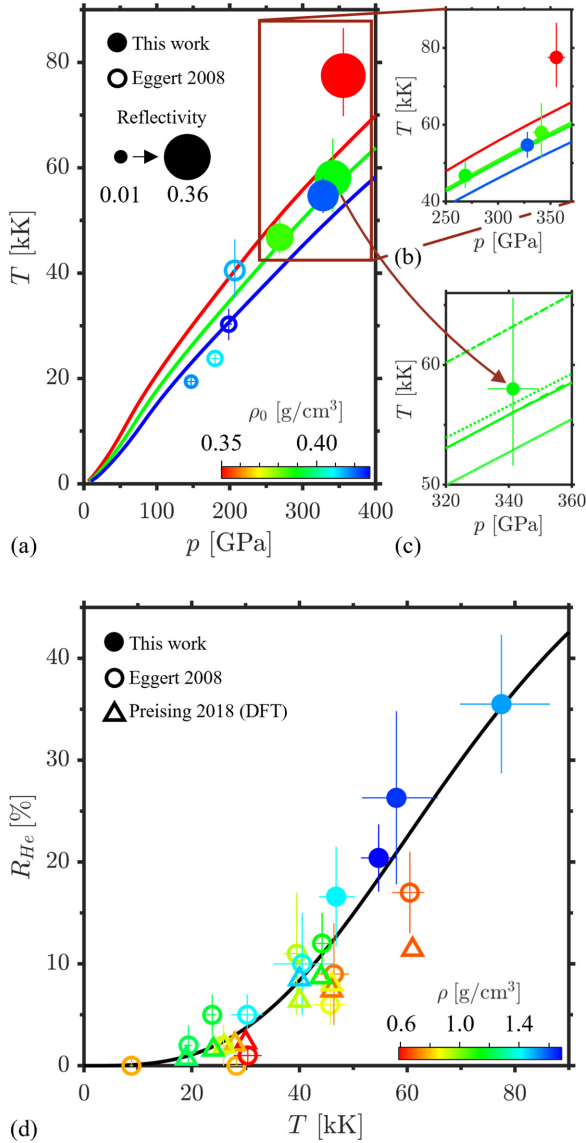


FIG. 6. (a) Temperature vs pressure in helium for the present work (closed symbols) and past work [12,41] reanalyzed in Ref. [42] (open symbols). Color indicates the precompressed density, while the symbol size indicates reflectivity. Three FPEOS Hugoniot curves [39] span the initial densities ($\rho_0 = 0.351, 0.389$, and 0.429 g cm^{-3}). (b) Close-up of the data and corresponding Hugoniot curves. (c) S74722 with Hugoniot curves from LEOS20 (long dashed) [36], SESAME5764 (dash dotted), SESAME5761 (dotted) [37], REOS (short dashed) [38], and FPEOS (solid) [22,25,39]. (d) Reflectivity vs temperature in helium for the present work (closed symbols) and past work (open symbols) [12,28,41,42,64]. The color in panel (d) only indicates shocked density.

characterization of quartz as a thermal standard, the shock velocities in the present work exceed the velocities of available data for which corrections for the effects of precompression have been determined [42]. Given that the precompression for the present work does not exceed 1.2 GPa, we utilize a model for the quartz temperature that neglects precompression but is otherwise valid for the present range of shock velocities [66]. Following Ref. [42], we estimate a correction for the effect of

precompression from the ratio of quartz temperatures given by models that either neglect or consider precompression,

$$\frac{T_{q,\text{cor}}}{T_{q,\text{uncor}}} = 1 - \frac{-14786 + 1555U_{s,q}}{1860 + 3.56U_{s,q}^{3.036}}(\rho_{0,q} - 2.65), \quad (4)$$

where $U_{s,q} = 20 \text{ km s}^{-1}$ is the maximum velocity for which both models are experimentally validated and densities are expressed in g cm^{-3} . Then, from Eq. (3), the corrected temperature in helium is given by

$$\frac{T_{\text{He,cor}}}{T_{\text{He,uncor}}} = \frac{\ln[(e^{T_c/T_{q,\text{uncor}}} - 1)I_q^*/I_{\text{He}}^* + 1]}{\ln[(e^{T_c/T_{q,\text{cor}}} - 1)I_q^*/I_{\text{He}}^* + 1]}. \quad (5)$$

The corrected temperature is reported in Table IV and Fig. 6, and the error is the sum of the standard deviation of the temperature from a moving average of the data with a window of 0.4 ns and the error propagated from the reflectivity measurement (i.e., the difference between the temperature calculated with the nominal reflectivity and the temperature calculated with the nominal reflectivity plus or minus the reported uncertainty). The agreement between the prediction of FPEOS and the data is generally good, as seen in Fig. 6(b). The measured temperature for S74727 exceeds the prediction of FPEOS, which may result from an overprediction of the reflectivity from our experimental fit to the present and preexisting data [12,41,42]. Figure 6(c) shows predictions from LEOS20, SESAME5764, SESAME5761, and REOS for S74722.

The temperature measurements further enable a prediction of conductivity according to the Drude-like model of Ref. [13]. The gap energy depends on density and temperature according to

$$E_g = E_0 - \left(A_0 + A_1 \frac{T}{T_0}\right) \frac{\rho}{\rho_{0,\text{He}}} - B \frac{T}{T_0}, \quad (6)$$

where $E_0 = 13.8 \text{ eV}$, $A_0 = 0.0260 \text{ eV}$, $A_1 = 0.820 \text{ eV}$, $B = 38.2 \text{ eV}$ [13], and T_0 and $\rho_{0,\text{He}}$ are provided in Table I. The electronic density is then calculated as

$$n_e = 2 \left(\frac{m_{\text{eff}} k_B T}{2\pi \hbar^2} \right)^{3/2} f_{1/2} \left(-\frac{E_g}{2k_B T} \right), \quad (7)$$

where $m_{\text{eff}} = 0.61m_e$ (m_e is the mass of an electron), k_B is Boltzmann's constant, $\hbar$ is the reduced Planck's constant, and $f_m(x)$ is the Fermi-Dirac integral of order m . The conductivity can then be calculated as

$$\sigma = 2 \frac{n_e e^2 \tau}{m_{\text{eff}}(1 - i\omega\tau)}, \quad (8)$$

where e is the charge of an electron, τ is the relaxation time in the Ioffe-Regel limit, and ω is the frequency of the 532-nm-wavelength probe laser. For S74727, S70906, S74722, and S72497, the dc conductivity is therefore determined to be 263, 93, 145, and 126 kSm^{-1} , respectively. These values significantly exceed previous measurements and provide further evidence of the increasing ionization in the present regime, where helium behaves like an electrically conducting fluid.

IV. CONCLUSION

Four experiments achieved extreme-pressure states in warm, dense fluid helium and show evidence of continuous ionization [20,24,25,33], with measured reflectivity exceeding 35% over pressures ranging from 270 to 360 GPa. Whereas previous data [41] appear to challenge the efficacy of DFT-MD calculations, the trends in the present data, including the increased compression likely caused by the onset of ionization [22], are captured by FPEOS, providing evidence that first-principles techniques can predict the EOS of warm dense helium in a regime where ionization becomes important. Although the measured temperatures in this work (40–80 kK) exceed those expected for helium-hydrogen phase separation in Jovian planets (~ 10 kK) [7,11], the high-pressure, high-temperature miscibility of helium and hydrogen remains incompletely understood. By increasing confidence in the behavior of dense pure helium and in the fidelity of DFT-MD simulations, this work provides a critical foundation for understanding such mixtures. Additional experiments utilizing greater precompression are ongoing to further document the effect of density and temperature on the insulator-to-metal transition in warm dense fluid helium.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX

Despite the use of antireflective coatings, the VISAR signal is polluted with reflection from the stationary diamond-sapphire interface, causing “ghost fringes.” To remove the influence of the stationary interface reflection, a fast-Fourier transform is performed in a temporal region of the VISAR signal after the unsupported shock front has weakened to the point of vanishing reflectivity, i.e., a region consisting exclusively of ghost fringes. The amplitude of the ghost fringes, assumed to be constant throughout the experiment, is then determined and subtracted from the signal, effectively removing the influence of the stationary reflection from the impedance matching analysis. More details on ghost fringe processing can be found in Ref. [57].

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- Correction:* Affiliation number 3 was presented incorrectly and has been fixed. The value given in the second sentence of the abstract has been fixed.