THERMOPHYSICAL PROPERTIES OF HELIUM UNDER MULTIPLE SHOCK COMPRESSION


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Abstract. The results on measurements of thermodynamic properties and electrical conductivity of Helium compressed with shock wave reverberation technique up to pressure and density of 200 GPa and 1.4 g/cc are presented. The increase of the Helium conductivity up to the values of 1000 1/(Ohm-cm) was found at the densities more than 0.7 g/cc and temperature more than 15 kK. Comparison of the experimental results with different theoretical models of thermodynamic and transport properties of shocked Helium was done.

INTRODUCTION

Being second after hydrogen in the set of element abundance in universe, helium attracts attention of theory due to simplicity of its atom structure. Thermophysical properties of helium in the Mbar pressure range at elevated temperatures (0.5-5 eV) are of interest to astrophysical researchers [1]. First and second ionization take place in this region. However, up to now only one dynamic experimental investigation have been performed [2]. On the basis of these experiments the semi-empirical EOS of helium [3] in the area of high density and pressure was improved. Authors of [2-3] did not consider ionization degree of shocked matter because of high value of first and second ionization energy (24.6 and 54.4 eV). Pressure of helium metallization at low temperatures is estimated about 11.2 TPa according to [3]. In a liquid state and at elevated temperatures pressures of the first and second ionization are considerably lower than that in solid state, as well as, to result in possible realization of these transformation in kinds of plasma phase transitions (PPT) [4-7].

FIGURE 1. T-P phase diagram of helium from [4] with traces of compression from 1D hydrocode (connected open squares). Predicted lines of constant mean charge are marked by its value. Tr –triple point, C–critical point. Tr3 – C1, Tr4 – C2 - PPT
Line of the assumed plasma phase transition of the first ionization in P-T diagram (Fig. 1) begins from triple point on the melting line with $P=200$ GPa, $T=1$ kK and finishes in critical point with $P=660$ GPa, $T=35$ kK [4].

In this paper we submit the results of simultaneous registration of optical emission and electrical resistance of a layer of helium under multiple shock compression to pressure 100 – 200 GPa, which is close to pressure of assumed plasma phase transition.

**EXPERIMENTAL SETUP AND RESULTS**

Experimental assembly was cooled by liquid nitrogen. Helium initial temperature was accepted equal 78 K - close to nitrogen boiling temperature. It was controlled by chromel-cupel thermocouple. Helium initial pressures and densities were varied in the range of 5-27 MPa and 0.03-0.12 g/cc. Stainless steel plates of thickness 1.5 - 1 mm accelerated by the explosive launching gun to velocity 5 - 8 km/s were used to generate megabar pressures. Layered systems [8,9] with PMMA intermediate layer allowed to obtain final velocities in the range of 6.5-8 km/s. Experimental technique used to measure optical emission and electrical resistance is analogous to that in [10-12].

![Figure 2](image)

**FIGURE 2.** Experimental snapshot with depicted moments of shock wave reflection.

1.2 – signals from $U_+$ and $U_-$ probe; 3 – brightness temperature ($T_{br}$) from pyrometer channels; 4 – $T_{br}$ from sensitive channel (its y axis is linear from 3 to 7 kK)

Three probe scheme was proposed for resistance of the helium layer measurements with shunt resistance being between charged probes. It has allowed to remove in-phase handicaps from measuring signal and identify the moment of shock wave reflection from the layer boundaries at the final stages of compression (Fig. 2). Time intervals were measured at the initial stages of compression with optical pyrometer also.

1D hydrodynamic simulation of the impact with EOS [3] was done. In Fig. 2,3 compression of helium with initial density $\rho = 0.0582$ g/cc is analyzed under impact of steel striker of thickness 1.5 mm with velocity 4.89 km/s on sandwich of steel bottom, helium layer, sapphire disk (thickness of 1, 5.28, 5.12 mm)

Thickness of the used steel striker was small relative to the initial helium layer thickness and process of compression was accompanied by unloading from bottom rear surface. This leads to the diminishing of the steel – helium boundary temperature and its optical emission during first shock wave passage.

There are two unloading waves in helium at first step of compression. Final thickness of helium layer was chosen to be bigger than 0.1 mm to avoid the shorting in an electrical circuit. It was 10-30 times smaller of the layer initial value. In the presented experiment hydrodynamic simulation gave the decrease of $T$, $P$, $\rho$ about 3, 7, 3 % during first compression of helium, due to rare release wave. At latter stages unloading wave from rare surface terminates the process of compression. This moment was indicated in emission record as a moment of transition to monotonically decreasing profile.

In the consideration of the process of compression manually was accepted, that in $P$ - $U$ coordinates Hugoniots of reflected waves in steel coincide with its isentrope and for sapphire –with its first Hugoniot. Time of first reverberation in steel bottom from optical record was used for estimation the time of compression termination. The bottom thickness was taken as the thickness of
FIGURE 3. P - U diagram of helium compression up to 114 GPa. 1 – sapphire Hugoniote; 2,3- steel isentropes; 4 -12 – manual path of compression; 13- hydrocode results.

compact material, flying away from striker after the impact. The counteraction of rarefaction waves was considered without taking into account materials strength.

P-U diagram of the process of compression in Fig. 2 is shown in Fig. 3. The parameters of compression according 1D code simulation are submitted also. In the first two - three steps of compression one can see closeness of parameters from both methods. Small decrease in experimental time of these steps leads to higher helium density relative to code results. This discrepancy is conserved up to the maximal pressures. Difference in final pressures is only about 4% while in density – about 20 %.

FIGURE 4. Experimental and code snapshot of helium of initial density 0.078 g/cc compression under impact of steel striker with velocity 8 km/s. Thickness of striker and sandwich layers are 1.02, 1.05, 1.145, 5.13 mm.

Usually code results were used to calculate density in the experiments with final pressure 150 – 230 GPa. It is connected with small value of compression step time intervals for a layer with thickness of about 2 mm. Such snapshot and code results are shown in Fig. 4.

As a rule, conductivity became more than 0.5 1/Ω/cm when the density was more than 0.7 g/cc. We were interesting in reversibility of the transition to states with high conductivity. It was measured density hysteresis of conductivity.

For illustration of a given thesis in Fig. 5 the experimental records of resistance change and brightness temperature profile (open circles) together with results of 1D hydrocode model density profile for first and end layer points (open and solid squares) for a given experiments are submitted.

FIGURE 5. Hysteresis of conductivity dependence on density. Open and solid squares – density profile near steel and sapphire; t1, t2 – time of conductivity increasing and decreasing.

DISCUSSION

The results of measurements of the electrical conductivity of helium dependence on density are placed in Fig. 6. In the experiments a wide spectrum of plasma states is realized: densities up to 1.5 g/cm³, temperatures ~(1-20)*10³ K at pressures ≤ 150 GPa and an electron concentration up to ~10²² cm⁻³. At maximal parameters the plasma is degenerated nₑλ³ ~ 50 and strongly nonideal in relation to the Coulomb interaction Γ = Eₑ/EEF ~ 10 and interatomic repulsion Γₐ = nₑλ³ ~ 1. The
electrical conductivity of plasmas is about 3 orders of magnitude increases within relatively narrow interval of densities (\(p\approx0.7-1.25\) g/cc), achieving the values of \(10^3\) ohm/cm typical to that of the heated alkaline metals.

\[ \sigma = \frac{n_e T^{3/2}}{\Lambda} \]

FIGURE 6. Helium conductivity versus density diagram.

Thermodynamical parameters of helium are calculated in frames of plasma chemical model [14], which takes into account Coulomb interaction in frames of Debye approximation in Grand canonical ensemble and repulsion of heavy particles using hard spheres approximation. The radii \(r=1.8\) a.u. was choisen from the coincidence of the calculated Hugoniots of liquid helium with the experiment [2]. To estimate conductivity we use \(\tau\)-approximation [4], which gives Spitzer asymptote for fully ionized Boltzmann plasma - \(\sigma = T^{3/2}/\Lambda\), \((\Lambda = \text{Coulomb logarithm})\) and in the case of the Fermi statistics - \(\sigma = T^{3/2}/\Lambda_F\). For the partially ionized plasma this theory gives Lorentz approximation: \(\sigma = n_e T^{3/2}/Q_{ea}\) (\(Q_{ea}\) - electron-atom transport cross-section).

The results of calculations for the different isotherms \(T = 10\) kK, \(T = 20\) kK, \(T = 30\) kK in dependence on density are placed in Fig. 6. At low temperatures decreasing of electrical conductivity with the increasing of density changed by its steep climb after some critical density. The main reason of this effect is so called pressure ionization that takes place at high densities. With the increasing of the temperature this effect becomes less apparent and disappears at very high temperatures. For the illustration of the dependence of the parameters on particle radii curves were calculated for \(r=1.3\) a.u. and \(T=10000\) K. It is seen that sharp increasing appears at more higher densities. The simplest Debye-Hückel approximation gives plasma phase transition at densities of \(\approx0.1\) g/cc (Curve DHA). More close to the experiment is Ebeling’s model [4].

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