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Dense plasma properties from shock wave experiments

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Abstract

A review is presented of the novel experimental results of investigation of physical properties of the coupled dense plasmas generated as a result of shock compression up to megabar pressure range. High-energy plasma states were generated by single and multiple shock compression. The highly time-resolved diagnostics permit us to measure thermodynamical, electrophysical and optical properties of high pressure condensed plasmas in the broad phase diagram region—from the compressed condensed solid state up to the low density gas range, including strongly coupled plasma and metal–insulator transition regions.

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Introduction

The physical properties of hot dense strongly coupled plasma at high pressures are of great interest for astro- and planetary physics, inertial confinement fusion, energetic, pulsed power technology and many other applications. The use of the intense shock waves technique in physical and chemical investigations has made the extreme state of plasmas an object of laboratory experiments and expands our basic knowledge to new exotic areas of the phase diagram of matter. This paper presents the modern results of experimental investigations of the thermodynamical, transport and optical properties of strongly coupled plasmas generated by intense shock waves.

Shock waves and nonideal plasmas

The use of intense shock waves in physical research has made an extreme state of matter and superhigh-speed processes the object of laboratory experiments. As a result of nonlinear hydrodynamics the narrow (a few interatomic distances) width of the viscous shock front transforms the kinetic energy of the flow into compression and irreversible heating of matter

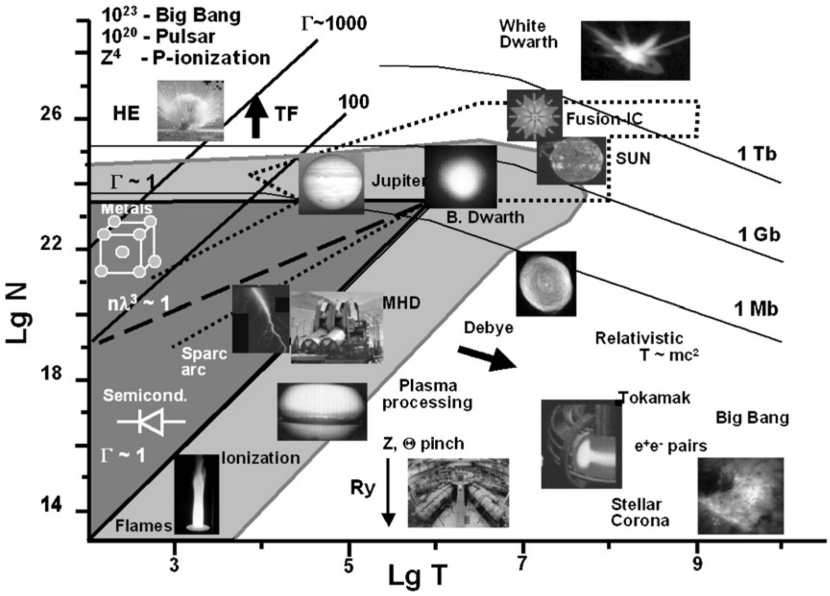


Figure 1. Plasma phase diagram [3, 4].

[1]. This method has no limitations in pressure but it has definite limitations in time scale which is typically $\sim 10^{-6}$–10^{-9} s. In addition, the application of the general laws of conservation of mass, momentum and energy enables one to reduce the recording of the thermodynamical characteristics of the matter under investigation to registration of the kinematic parameters of the propagation of shock fronts and interfaces [2, 3] (i.e. to the time and distance measurements).

Strongly coupled plasmas occupy a very broad region of the phase diagram of matter [3, 4], as illustrated in figure 1, where

$$\Gamma = \frac{\sqrt{2\pi} e^3}{(kT)^{3/2}} \sqrt{\sum_i Z_i^2 n_i} \qquad \text{and} \qquad \lambda = \sqrt{\frac{\hbar^2}{2\pi kT}}$$

are the coupling parameter and the de Broglie wave length, respectively. The physical properties of plasmas become simple in two asymptotic cases—at extremely high pressures and extremely high temperatures. In the first case, the inner electronic levels of atoms and ions are compressed by pressure and one can apply the Thomas–Fermi theoretical model. In the other extreme state—high temperature and low density—the interparticle interaction is small and one can apply the quasi-ideal gas-like Debye–Hückel approach.

The subject of our interest is the strongly nonideal plasma which is located just between these two asymptotes where interparticle interaction is much greater than kinetic energy of motion.

This exotic state of matter is a very difficult subject for theory because the strong interparticle interactions are realized in a disordered system with electron statistics intermediate between Boltzmann- and Fermi-like types. On the other hand, it is rather difficult to create a strongly nonideal plasma under laboratory conditions because it is necessary to cumulate high-energy densities in condensed matter at high pressures and temperatures [3–7].

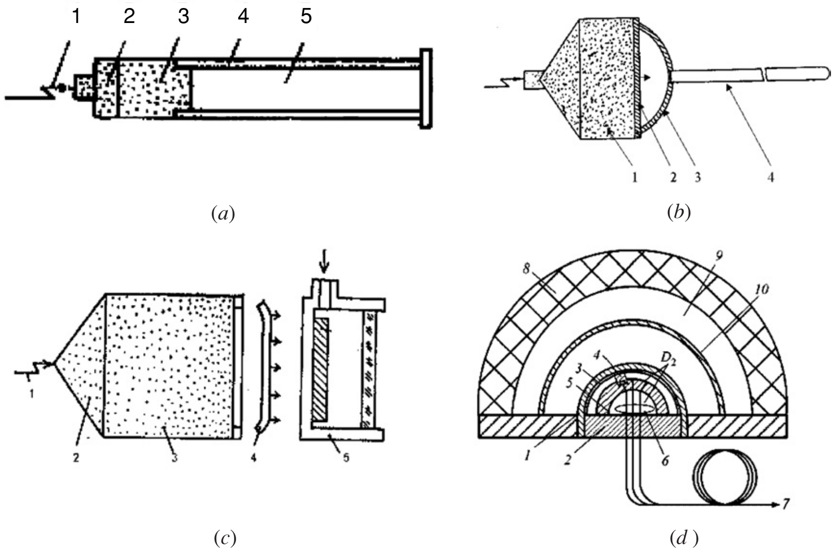


Figure 2. (*a*) Linear explosively driven shock tube. 1—detonator, 2—high explosive lens, 3—high explosive, 4—glass tube, 5—investigated gas. (*b*) Voitenko compressor. 1—high explosive, 2—flying plate, 3—compression chamber, 4—glass tube. (*c*) HE gun. 1–detonator, 2—high explosive lens, 3—high explosive, 4—flying plate, 5—experimental vessel. (*d*) Hemispherical experimental device. 1—frame, 2—base, 3—screen, 4—sample, 5—housing, 6—optical sensors, 7—measuring line, 8—explosive, 9—air gap, 10—impactor.

Generations and drivers

To generate strongly coupled dense plasma by intense shock waves a broad spectrum of drivers is used—chemical and nuclear explosives, pneumatic and electrical guns, intense laser and soft x-rays, electrons, and light- and heavy-ion beams.

The first measurements of equation-of-state data and electrical conductivities of nonideal plasmas were carried out with pneumatic shock [8] and adiabatic [9] compression tubes. To increase the initial saturation of caesium vapour density the experimental devices were heated up to an initial temperature of $\sim$900 °C.

Because the high explosives have a specific energy density six orders of magnitude higher than electrical capacitors, most experiments in shock compression of plasmas were carried out using these drivers. In the explosively driven shock tubes the intense shock wave is generated in the precompressed noble gases as a result of expansion of detonation products of high explosives [3, 4, 10]. To realize velocities of shock in the range 8–30 km s^{-1} 'linear' and cumulative explosively driven shock tubes were used (figures 2(*a*) and (*b*)). Measurements of EOS, electrical conductivity and opacity of nondegenerate Boltzmann-like coupled plasmas at pressures up to 200 kbar were carried out using these devices [3, 4, 10].

Much higher $\sim$1 Mbar pressures in gases and $\sim$5 Mbar in metals were generated by high explosive guns [4, 11] (figure 2(*c*)). In this device high explosive detonation products accelerate a metal impactor up to the velocity of $\sim$5–6 km s^{-1}. The impact of this high velocity impactor against a target generates a plane shock wave in plasmas with pressures up to a few Mbar. The lifetime of these high pressure plasma states is rather short because of the inertial confinement. As a result, the diagnostic for those experiments must be sufficiently fast.

Electrical pin and optical base methods; optical reflectivity, spectrometry and pyrometry; x-ray diffraction and absorption; laser interferometry; electrical resistivity, capacitor and piezoelectricity methods and other diagnostic methods applied to shock experiments must have temporal resolution better than $\sim 10^{-6}$–10^{-9} s.

To increase shock pressure the front collision generator was designed. In this device the materials under investigation are compressed from two sides by two strikers accelerated by high explosive charges which were ignited simultaneously [12].

To increase launch velocity and shock pressure in plasma some sophisticated gasdynamic ideas were applied.

The idea of plane gradient cumulation is very similar to acceleration of a light ball which elastically strikes a heavy one. As a result, a 3-stage high explosive gun accelerates the molybdenum projectile up to 13–14 km s^{-1} [13].

Spherical high explosive generators (figure 2(*d*)) were designed in the Soviet Union in the late 1940s and were used to reach pressures up to 10–20 Mbar as a result of spherical cumulation [14]. The weight of this system is as high as 100 kg and energy release is $\sim$500 MJ. The maximum spherical projectile velocity was as high as 20 km s^{-1}.

The more stable explosive-driven system based on irregular Mach-type collision of conical shocks was used for measurement of shock Hugoniots and isentropes of metal plasmas [15]. Combination of nonregular shock collisions with gradient cumulation allows the generation of 20 Mbar shocks in copper, which is close to the pressure typical for nuclear explosions.

In magnetic cumulation generators high explosive detonation compresses a magnetic field in cylindrical geometry, which in turn adiabatically compresses samples up to a few megabars [16]. High magnetic field experiments were performed recently to measure the Hall effect parameters in dense shock-compressed plasmas [17].

In recent decades, as a result of detente and changing defense priorities, some new drivers based on pulsed power principles were applied to shock wave research.

To investigate shock wave dynamics, hypervelocity impact phenomena and penetration physics at high pressure rail guns have been used [18]. In this device a solid plastic projectile is accelerated up to the velocity of $\sim$8–9 km s^{-1} as a result of electromagnetic interaction of a plasma arc with one MA pulsed current.

Relativistic electron beam generators were used for intense shock excitation in metals and for volumetric heating of low density foams. The registration of shock wave dynamics in the metal target allows us to investigate the influence of self-generated intense magnetic field on the stopping power of electrons in dense plasmas [19].

Much higher energy densities were generated by intense light-ion beams and relativistic heavy-ion beams. The high current pulsed proton beam accelerator KALIF generates a power density on target of $\sim 10^{12}$ W cm^{-2}. This pulsed power installation was used to accelerate thin metallic and plastic foils to velocities up to $\sim$12–14 km s^{-1} for investigation of the stopping power of protons in dense plasmas, for measurements of the equation of state and material viscosity at megabar pressures and for measurements of spallation strength of the materials at ultrahigh strain rates [20].

The heavy relativistic ion beam accelerators constructed for investigations of nuclear collisions at ultrahigh energy densities appear to be effective drivers for ICF projects for shock wave and dense plasma physics research. The heavy-ion beams with a kinetic energy of $\sim$1 GeV were used for investigation of beam–plasma and beam–solid interactions [21] and with a kinetic energy of several MeV for stopping power measurements in nonideal plasmas [22].

The world record in shock pressure among laboratory devices belongs now to the laser-driven shock wave technique [23, 24]. Valuable results in this field have been obtained recently by the strong scientific teams of Livermore, Osaka, Garching, Milan and Moscow.

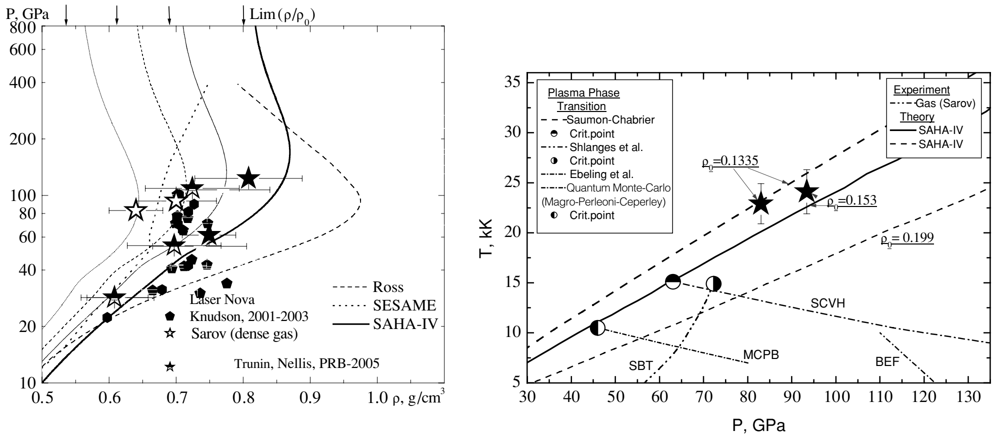


Figure 3. Hugoniots of dense deuterium [32].

In x-ray driven shock experiments [25], a pulsed 4 MA current accelerates a cylindrical plasma liner up to the velocity of $\sim$500 km s^{-1}. The impact of this liner against a cylindrical target generates a radiation thermal wave which heats the inner cavity up to a temperature of $\sim$100 eV. The soft x-rays from the plasma cavity were used for generation of shock waves of 5 Mbar pressure, for the acceleration of the metal striker and for radiative shock wave investigations.

Plasma under extreme conditions

The first obtained experimental information on nonideal plasma thermodynamics was quite surprising [4, 8, 26] and showed how hazardous it is to extrapolate to high pressure the results and views obtained for low pressure. Shock experiments have shown that the pressure of a strongly coupled plasma at constant temperature and/or enthalpy is much higher than the ideal pressure while, according to standard plasma textbooks, this pressure should be less than ideal due to plasma polarization. The interpretation of the data obtained has shown that at least two different physical effects are responsible for the unusual thermodynamics—the screening of the charged particles (electrons and ions) and the deformation of the discrete electron energy spectrum as a result of strong interparticle interactions.

The sophisticated family of theoretical models based on superposition of plasma ionization approaches and solid state cell models was developed to describe the shock wave experiment in a broad region of the plasma phase diagram [3, 27–30]. The shock Hugoniot for Al shows how plasma theoretical models describe the shock experiment in a broad region of parameters up to extremely high pressure of $\sim$4 Gbar obtained in underground nuclear experiments [31]. Note that at this super-high pressure the specific energy of the plasma is about 1 GJ cm^{-3} which is close to nuclear explosion energy density, and the pressure of photon radiation is close to kinetic pressure. This is why it is meaningless to increase the shock pressure above that limit.

The description of plasma thermodynamics obtained using classical plasma physics for the nontraditional region of high temperatures in the condensed state is illustrated by deuterium Hugoniots (figure 3) [32]. Calculations in the modified plasma chemical model [30, 32] show that the states arising behind the shock-wave front in the experiments [32–36] correspond to a dense strongly nonideal ($\Gamma_D \sim 1$), partially ionized ($n_e/n_D \sim 1$), partially degenerate ($n_e\lambda^3 \sim 3$) and practically isothermic ($T \sim$ 22–24 kK) deuterium plasma with the pressures

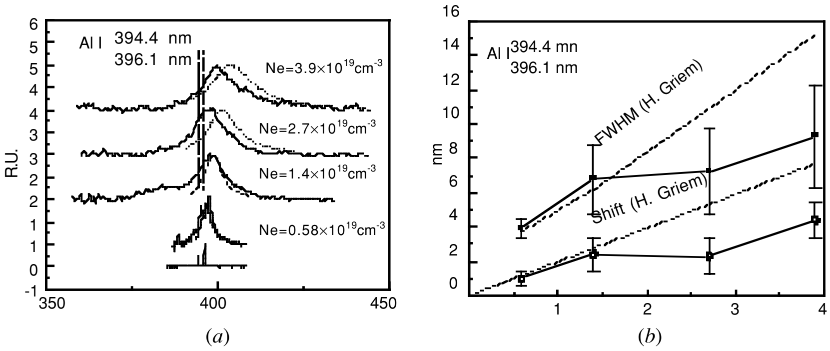


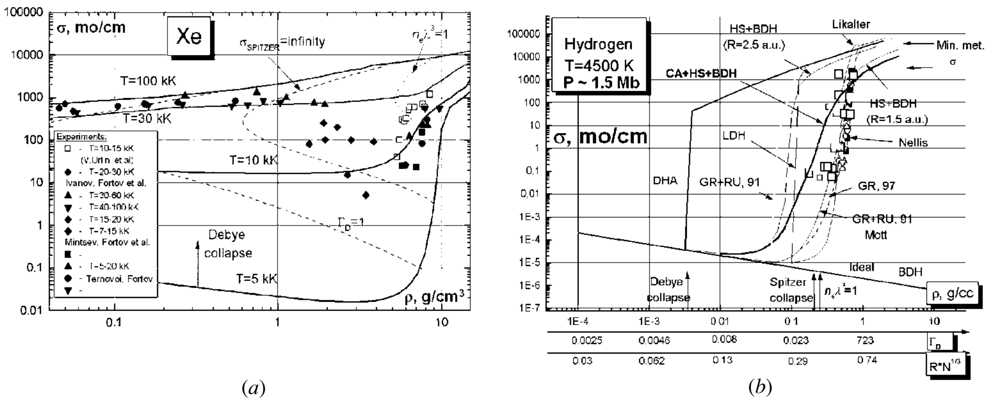
Figure 4. (*a*) The contours of Al lines in Xe plasma and (*b*) the width and shift of Al lines.

about 1 Mbar. It is worth noting that this theoretical model agrees with the results of the experiments on the shock compression of preliminarily compressed gaseous deuterium [32] and with the results of the shock compression of liquid and solid deuterium [33–36].

The opacity measurements for strongly coupled plasmas are also rather surprising [37]. In contrast to the classical textbook predictions, shock wave experiments have shown that as a result of compression the plasma becomes more and more transparent rather than opaque [3, 27, 37, 38]. The explanation of this effect is based on the shift of discrete energy levels to the continuous spectrum as a result of strong interparticle interaction. To describe this effect theoretical models based on the 'confined atom' approach or on plasma fluctuating microfields were applied [3, 26, 27]. The registrations of the optical emission of hydrogen [37] and xenon [39] shock-compressed plasmas have shown that most of the spectral lines of strongly nonideal plasmas are destroyed by strong particle interactions. This fact is illustrated in figure 4(*a*), which presents the form of the observed lines of aluminium admixture in xenon plasma in dependence on density [40]. The vertical stroke lines demonstrate the position of undisturbed lines and also dotted contours of lines; these are the contours calculated by Stark tables for neutral atom isolated lines. Figure 4(*b*) shows the broadening and shift dependence of the lines on concentration of electrons. The experimental data for the electron densities $n_e < 1.3 \times 10^{19}$ cm^{-3} are in good agreement with theory and the maximal relative disagreement between them was found to be for $n_e > 2.4 \times 10^{19}$ cm^{-3}.

Electrical conductivity measurements allow us to obtain experimental information about plasma composition at high pressure because the conductivity is closely connected with free electron concentration and electron scattering in coupled plasmas. To investigate the 'thermal' ionization, experiments on shock compression of heavy noble gases were performed [30, 41]. The measured xenon plasma electrical conductivity was very high and close to the conductivity of alkaline metals, as illustrated in figure 5(*a*). It is interesting that the measurements were performed at extremely high densities where extrapolations of standard plasma theoretical models show meaningless results—so-called Coulomb collapse predicted by Wigner [42] and Spitzer collapse due to overestimation of Coulomb scattering [27].

In shock compressed hydrogen plasma [30, 43–45] (figure 5(*b*)) the temperatures are much lower than that of xenon plasma. This allows us to investigate more definitely pressure ionization effects due to lowering the ionization potential as a result of strong interparticle interaction and overlapping atomic wavefunctions in strongly coupled plasmas [30]. Nowadays, we are trying to measure the EOS of hydrogen plasma carefully to understand, there are plasma transitions which were predicted by theory [27]. At least the experimental measurements obtained for electrical conductivity do not contradict this plasma phase transition hypothesis.



(*a*) (*b*)

Figure 5. (*a*) Conductivity–temperature ionization of Xe plasmas [30]. (*b*) Conductivity–pressure ionization; hydrogen plasma at megabars [30].

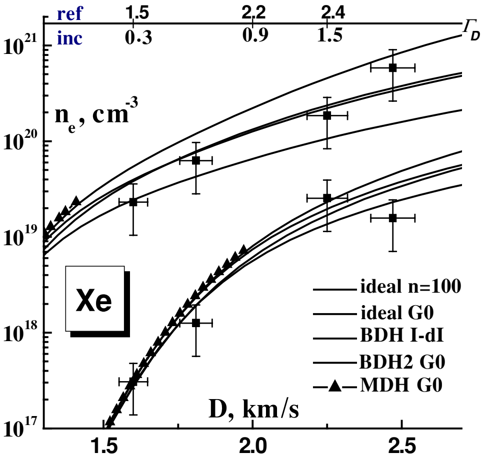


Figure 6. Electron density of nonideal xenon plasma [17].

The electron density and dc electrical conductivity of dense partially ionized plasma of argon or xenon placed in magnetic field were measured in [17]. Plasma was generated behind the front of incident and reflected shock waves with the help of linear explosively driven tubes. The measurements were performed at $P = 30$–650 MPa, $T = 6$–17 kK, Coulomb coupling parameter $\Gamma = 0.01$–2.8. Electron density was calculated from measured values of Hall potential difference. The comparison of experimental results with different models of thermodynamic and transport properties of nonideal xenon plasma is shown in figure 6. Where D is the front velocity of incident shock wave, the lower groups of curves and dots correspond to incident wave, upper curves reflected. The comparison of measured values of conductivity and electron density with calculated values shows that calculated values are consistent with experiment when a Debye approximation is used in the grand canonical ensemble or the approach of an ideal plasma with partition functions restricted by the ground state.

The results of measurements of the dense xenon plasma reflection coefficient at the three wavelengths $\lambda = 532$, 694, 1064 nm are presented in figure 7 [46]. The investigation of reflective properties of the plasma was accomplished within the wide range of plasma densities

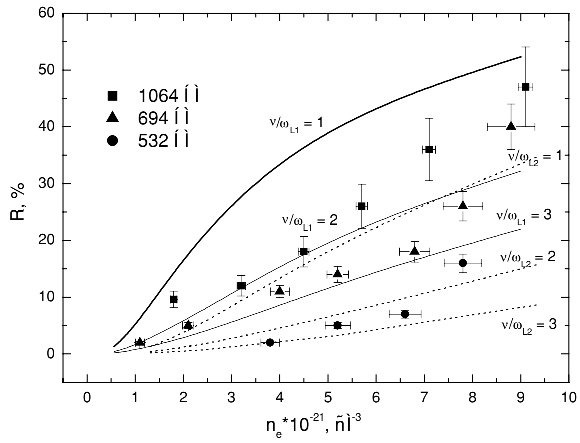


Figure 7. Reflection coefficient versus electron concentration [46].

$\rho = 1$–4 g cm^{-3}, pressures $P = 4$–20 GPa and temperatures up to $T \sim 3 \times 10^4$ K under conditions with strong Coulomb interaction (the nonideality parameter $\Gamma = e^2/kTr_D = 3.6$–6.5). In the same figure computational curves in accordance with the Drude relation for high-frequency conductivity at $\nu/\omega_L =$ const are shown with the suggestion that the thickness of the shock-wave front is smaller than the laser beam wavelength. This fact justifies applying the Fresnel formulae for the reflection coefficient. The measured optical reflectance coefficient of shock-compressed dense plasma does not agree with a simple Drude model for any reasonable collision frequency value. On the basis of the assumption of local thermal equilibrium, it is not possible to interpret the measured values of the dense xenon plasma reflection coefficient at different wavelengths within the assumption of a step-like density profile. More reasonable results are obtained after numeric solution of the equation for electromagnetic fields with the static collision frequency in Born approximation assuming an electron density profile with characteristic width about 800 nm.

Conclusions

In this paper, because of space limitation, we were able to discuss and to cite only the research areas and articles where we worked personally and which are close to us. Much more information on shock wave physics can be found in numerous review articles and books (see [1–46] and references therein).

Acknowledgments

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