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Intense shock waves and extreme states of matter

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Contents

Abstract. The physical properties of hot dense matter over a broad domain of the phase diagram are of immediate interest in astrophysics, planetary physics, power engineering, controlled thermonuclear fusion, impulse technologies, enginery, and several special applications. The use of intense shock waves in dynamic physics and high-pressure chemistry has made the exotic high-energy-density states of matter a subject of laboratory experiments and enabled advancing by many orders of magnitude along the pressure scale to range into the megabars and even gigabars. The present report reviews the latest experimental research involving shock waves in nonideal plasmas under conditions of strong collective interparticle interaction. The results of investigations into the thermodynamic, transport, and optical properties of strongly compressed hot matter, as well as into its composition and conductivity, are discussed. Experimental techniques for high energy density cumulation, the drivers of intense shock waves, and methods for the fast diagnostics of high-energy plasma are considered. Also discussed are compression-stimulated physical effects: pressure-induced ionization, plasma phase transitions, the deformation of bound states, plasma blooming ('transparentization' of plasma), etc. Suggestions for future research are put forward.

1. Prologue

It is a great honor for me to take part in the special scientific session of the Editorial Board of the journal *Uspekhi Fizicheskikh Nauk* dedicated to the jubilee of our outstanding compatriot Vitalii Lazarevich Ginzburg, whose personality and works have largely foreordained the contemporary level and progress of the physical sciences in our country. I, then a first-year student of the Moscow Institute of Physics and Technology, was profoundly impressed by the review lecture dedicated to extreme astrophysical processes which Vitalii Lazarevich delivered in 1962. Over the years, the personality of this remarkable man has significantly influenced, directly or indirectly (primarily via Lev Vladimirovich Al'tshuler (in the center in the photograph), David Abramovich Kirzhnits, Evgenii Grigor'evich Maksimov and, of course, via the Seminar [1]), the kind and direction of my scientific preferences.

Photograph. At the dawn of the nuclear era (left to right): Vitalii Lazarevich Ginzburg, Lev Vladimirovich Al'tshuler, and Veniamin Aronovich Tsukerman (Arzamas-16 (Sarov), at V A Tsukerman's house, 1955).

When preparing for this session of the Editorial Board, we agreed to adhere to the 'list at the beginning of the XXI century', the 'physical minimum', which was formulated by Vitalii Lazarevich in his Nobel Lecture. That is why here I touch upon items 3, 5, and 9 of this list: 3 — 'metallic

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[1] See the footnote on p. 331 of this issue of *Phys.-Usp.* (*Editor's comment*).

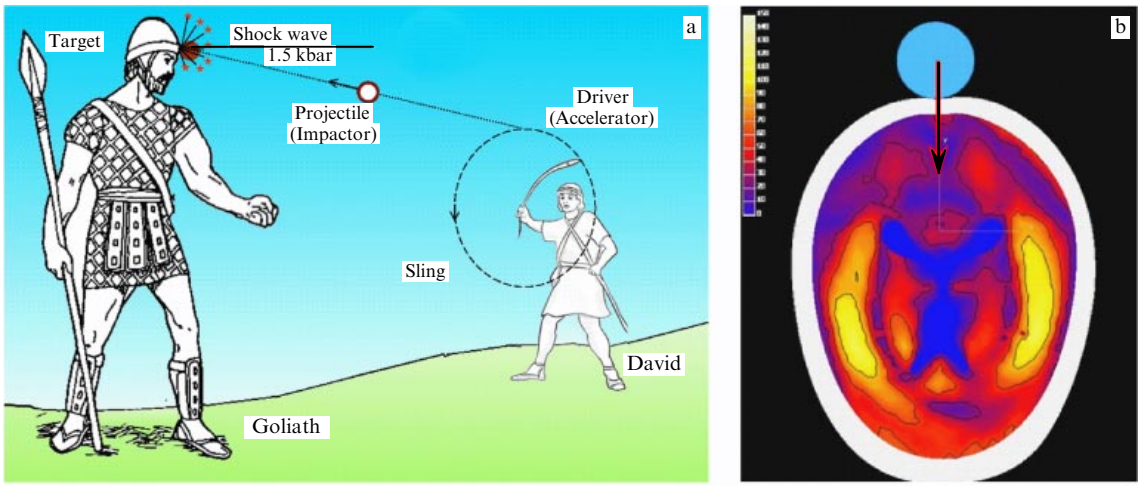


Figure 1. Battle between David and Goliath [1], approximately 1000 B.C. The Bible, the Old Testament, 1 Sam. 17: (a) schematic representation of the battle, (b) two-dimensional computer simulation of the blow (shock) of the stone on Goliath's head, which was shot from David's sling (the diameter of the stone $\sim$ 10 cm, its mass $m \sim 500$ g, and its velocity $w \sim 20$ m s^{-1}).

hydrogen, other exotic substances'; 5 — 'some questions of solid-state physics, metal – dielectric transitions'; and 9 — 'fullerenes'.

We will deal with experiments involving intense shock waves. Foundation of this experiments was laid by Prof. Al'tshuler, an old friend and colleague of Ginzburg and my teacher, whose works established a new scientific field — dynamic high-pressure physics.

Although I do not intend to delve deeply into the history, there is no escaping several historical remarks. According to historical investigations, the first successful experiment (Fig. 1) involving intense shock waves was supposedly conducted more than 3000 years ago — during the battle between David and Goliath [1][2].

According to the Old Testament [1] and the subsequent two-dimensional gas-dynamic calculations on a supercomputer (Fig. 1b), the high-velocity impact of a stone, which was shot from David's sling, on Goliath's head gave rise to a shock wave in Goliath's head with an amplitude pressure of $\sim$ 1.5 kbar. This pressure was more than two times higher than the strength of Goliath's frontal bone, which determined the outcome of the duel, to the great joy of the army and people of Israel.

Discovered to be successful at that time, this scheme of action (Fig. 1a) serves as the basis for all subsequent experiments in the area of dynamic high-pressure physics.

The use of higher-power and more sophisticated acceleration schemes — chemical and nuclear explosives; gunpowder, gas, and electrodynamic 'guns'; charged particle, laser radiation, and X-ray fluxes; etc. — has enabled, since the biblical time of David, increasing the projectile velocity by three to four orders of magnitude and the shock pressure by six to eight orders of magnitude to reach pressures ranging into the megabars and gigabars.

The main development of the physics of shock waves in the 20th century was intimately related to the entry of our civilization into the atomic, space, and aviation eras. Strong shocks play an important part in the hypersonic flights of aircraft and rockets, as well as in the entry of spacecraft into the planetary atmospheres of the Solar System. In nuclear bombs, intense shock waves are employed to initiate chain nuclear reactions in a compressed nuclear fuel. In thermonuclear charges and in controlled fusion microtargets, shock and radiative waves are the main tools for the compression, heating, and triggering of thermonuclear reactions.

In the Soviet Union, the scientific school in the area of intense shock waves and high energy density physics was established by the Nobel Laureate academician N N Semenov. The main contribution to this area was made by our outstanding scientists Lev Vladimirovich Al'tshuler, Yakov Borisovich Zel'dovich, Yulii Borisovich Khariton, and Andrei Dmitrievich Sakharov. Two of them — Al'tshuler, an experimenter, and Zel'dovich, a theorist – are the real 'fathers' of the physics of shock waves in condensed media [2, 3]. I have the great honor to have been since 1964 a pupil and later on a colleague of these outstanding personalities and scientists who I have happened to cooperate with in this fascinating and multifaceted area. The basic principle of scientific work was formulated by Yulii Borisovich Khariton: "We have to know at least ten times more in basic physics than is pragmatically necessary to solve the technical problems".

The aim of this report is to outline several recent scientific results in studies of a dense nonideal high-pressure plasma with the help of intense shock waves and to discuss the prospects for the future.

2. Shock waves and extreme states of matter

The study of a strongly compressed hot substance (plasma) is of interest for applications as well as for basic science. The use of high-pressure plasmas is associated with the development and realization of several promising power-producing projects and devices like mobile nuclear reactors and nuclear space propulsors, magnetohydrodynamic and magnetocumulative generators [4], and devices for controlled and 'semicontrolled' nuclear fusion [5], in which the compressed plasma plays the same part as compressed water vapor in 19th century heat engines. These and several other applications are a permanent pragmatic incentive to study substances under ultrahigh pressures and temperatures.

[2] Knowing academician Ginzburg's special interest in the 'evergreen' subject of the relation between science and religion, the first reference of this review is made to the Old Testament.

Apart from applications, the study of strongly compressed plasmas enriches our general scientific notions about the fundamental properties of matter [6], because about 98% of the matter in the Universe (without 'dark matter' if it exists) is in the compressed hot baryon state. Brown dwarfs, pulsars, supernova, X-ray sources, giant planets, and the recently discovered extrasolar exoplanets consist of huge masses of hydrogen, helium, and other substances compressed by gravitational forces to tremendous pressures. Shock waves play the decisive role in the laboratory study of these states today.

Shock waves offer at least two significant advantages in studies of a strongly compressed plasma:

(1) Not only do shock waves compress the plasma, but they also heat it to produce its thermal ionization, as well pressure-induced ionization.

(2) Because of inertial confinement of the shock-compressed substance, dynamic techniques enable producing extremely high pressures and temperatures unattainable under static conditions.

That is why shock-wave techniques play the leading role in high energy density physics today [2–9], making it possible to produce amplitude pressures of the megabar and gigabar range for many chemical elements and compounds. This range of peak dynamic pressures is six orders of magnitude higher than the pressure in Goliath's head upon the stone's impact (see Fig. 1) and three orders of magnitude higher than the pressure at the center of the Earth, and is close to the pressure at the center of the Sun and in inertial confinement fusion targets [5, 6]. These exotic states of matter were realized during the birth of our Universe, within several seconds after the Big Bang [4, 6] (Fig. 2). In a sense, we cans say that by progressively increasing the pressure and temperature in laboratory experiments it is as if we travel backwards on the time axis to approach the instant of creation of the Universe — the Big Bang.

3. Nonideal plasma

The subject of our report is a hot dense matter in conditions of strong interparticle interaction — the so-called nonideal plasma, in which the intense interparticle interaction defines its physical properties — thermodynamics, composition, conductivity, radiative and optical properties, and the stopping power of charged particles [4].

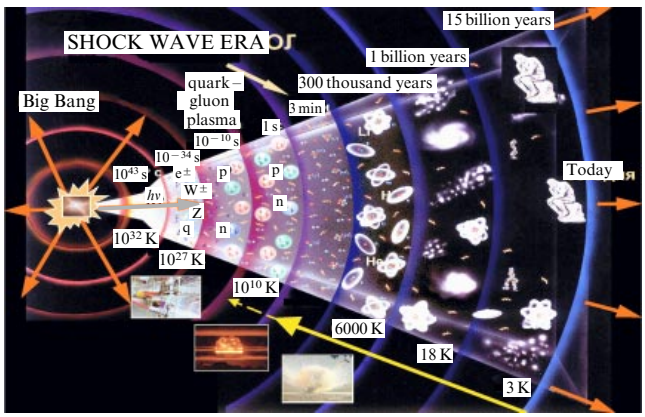


Figure 2. Time scale after the Big Bang (K Rubia, private communication).

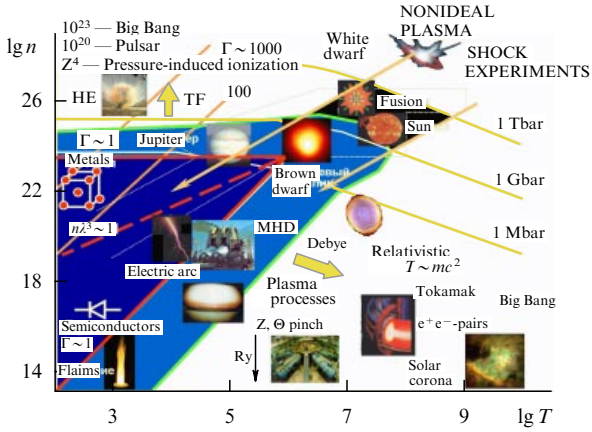


Figure 3. Phase diagram of matter.

The nonideal plasma occupies a broad domain in the phase diagram of matter (Fig. 3). For a physical description of the properties of this plasma two dimensionless parameters, Γ and $n\lambda_e^3$, are commonly used.

The Coulomb interparticle interaction between the charges Z_i and Z_j in a plasma with a density $n \sim r^{-3}$ describes by $Z_i Z_j e^2 n^{1/3}$. The nonideality parameter

$$\Gamma = \frac{Z_i Z_j e^2 n^{1/3}}{E_k}$$

characterizes the ratio between the Coulomb interaction energy and the kinetic energy E_k of particle motion.

Quantum degeneracy effects are described by the dimensionless parameter $n_e \lambda_e^3$, where $\lambda_e = [\hbar^2/(2\pi mkT)]^{1/2}$ is the thermal de Broglie wavelength of the electron.

For the classical Boltzmann statistics (when $n\lambda^3 \ll 1$), the scaler of kinetic energy is $E_k \sim kT$ and this plasma becomes more and more nonideal under compression.

In the limit of high-density plasma, the electrons become degenerate, $n\lambda^3 > 1$. For the quantum statistics, the scale of kinetic energy is the Fermi energy $E_k \sim \hbar^2 n^{2/3}/2m$. That is why a degenerate plasma becomes more and more ideal as a result of compression. In our shock experiments we are capable of producing both the Boltzmann and Fermi nonideal plasmas.

We see that the physical plasma properties are simplified in two limiting cases: at high temperatures and at high pressures. In the first case (high temperatures and low densities), the interparticle interaction is weak ($\Gamma \ll 1$) and the ideal gas approximation applies. In the other limiting case of high densities, the inner electron shells of atoms and ions are 'crushed' by pressure, which justifies the application of the Thomas–Fermi model and then the uniform ideal ($\Gamma \ll 1$) electron Fermi gas.

Of concern to us is the area between these asymptotics, where the interparticle interaction energy exceeds the kinetic particle energy ($\Gamma > 1$).

Until recently, the majority of plasma investigations pertained to low-density high-temperature ideal plasma, where $\Gamma \ll 1$. In this case, the plasma electrons may be treated as an ideal classical or quantum gas and the Coulomb screening effects may be described by the perturbation theory [4]. A more complicated and interesting regime corresponds to a 'nonideal' plasma possessing a high density and a 'low'

temperature, where $\Gamma > 1$. In such a plasma, ions are strongly correlated and the electrons partly degenerate: $n_e \lambda_e^3 > 1$. This plasma may no longer be treated as a quasi-ideal gas and therefore cannot be described by perturbation theories. Theoretically, such an exotic state of matter is an extremely arduous subject due to a strong interparticle interaction in a disordered medium with intermediate (between the Fermi and Boltzmann statistics) types of electron statistics [4, 6].

On the other hand, a nonideal plasma is an inconvenient subject for experiments as well: its production requires the cumulation of high energy densities in a dense medium at high temperatures and pressures. The shock technique turns out to be the most appropriate tool for the purpose.

4. Shock-wave compression

To produce a strongly compressed plasma with extremely high temperature and density, we use intense shock waves [4, 7–9] arising from nonlinear hydrodynamic effects in the motion of matter. In a viscous compression shock termed the shock front, the kinetic energy of the oncoming flow is converted to the thermal energy of the compressed and irreversibly heated medium (Fig. 4). This way of shock compression (the Hugoniot adiabat in Fig. 5) has no limitations in the magnitude of the pressure obtained but is bounded by the short lifetimes of the shock-compressed substance. That is why the techniques employed for the diagnostics of these states should possess a high ($\sim 10^{-6}$–10^{-9} s) temporal resolution. It is precisely this temporal resolution that is inherent in the electrocontact and optical recording of the time intervals in the motion of shock-wave discontinuities and contact surfaces; in the pyrometric, spectroscopic, X-ray diffraction and adsorption, and laser interferometric measurements, as well as in the recording of low- and high-frequency Hall conductivity; and in the detection of piezo- and magnetoelectric effects [4, 7–9].

A characteristic feature of the shock technique is that it permits obtaining high pressures and temperatures in compressed media, while the low-density domain (including the boiling curve and the neighborhood of the critical point) turns out to be inaccessible to it. Investigation of the plasma states intermediate between a solid and a gas is made by the isentropic expansion technique. This technique involves the generation of plasma in the adiabatic expansion of a condensed substance (curve S in Fig. 5) precompressed and irreversibly preheated at the front of an intense shock wave.

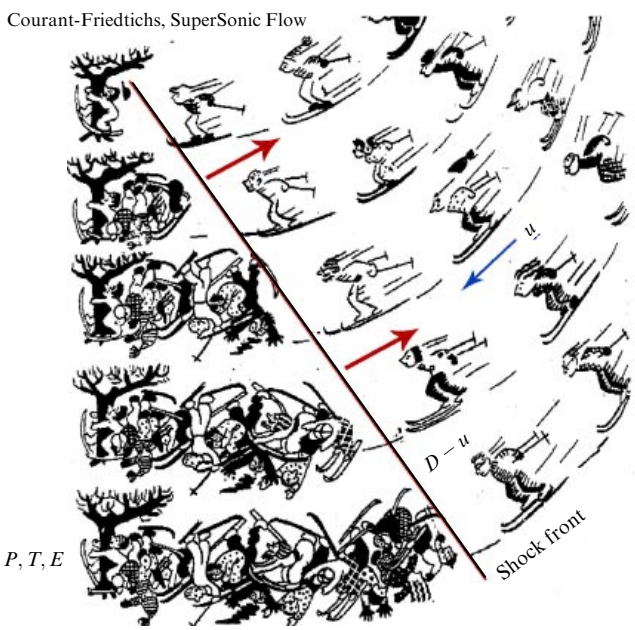


Figure 4. Shock-wave compression and the heating of a substance.

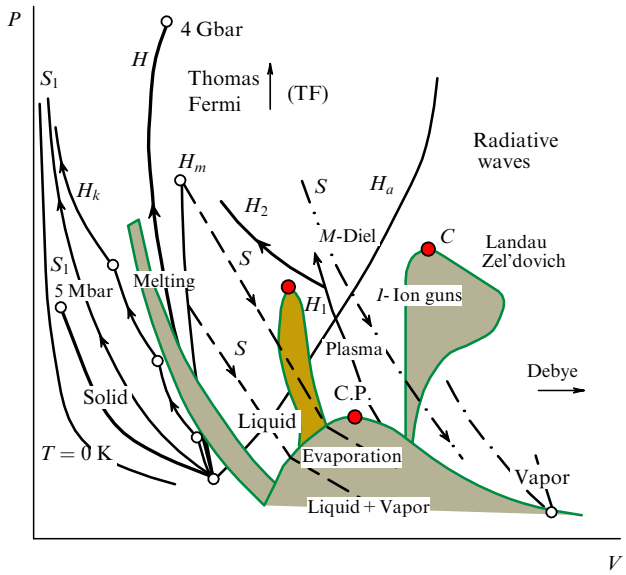


Figure 5. Phase diagram of matter [4, 7–9]. H — Hugoniots, S — isentropes. Phase boundaries are sketched. C.P. — critical point.

We see that dynamic techniques in their different combinations permit realizing and investigating a broad spectrum of plasma states with a variety of strong interparticle interactions. In this case, not only does the actual realization of high energy density conditions turn out to be possible, but so does sufficiently thorough diagnostics of these states, because shock and adiabatic waves are not merely a means of production, but a specific tool for the diagnostics of extreme states of matter as well [2, 3, 10].

Dynamic diagnostic techniques rely on the relation between the thermodynamic properties of a shock-compressed medium under investigation and the experimentally observed hydrodynamic phenomena occurring in the cumulation of high energy densities in the substance [2, 3]. In the general form, this relation is expressed by a system of nonlinear (three-dimensional in spatial coordinates) differential equations of gas dynamics, whose complete solution is difficult even with the most powerful modern supercomputers. This is the reason why in dynamic investigations efforts are made to employ self-similar solutions like a stationary shock wave and the centered Riemann rarefaction wave [2, 3], which express the conservation laws in simple algebraic or integral forms. In this case, in order for these simplified relations to be applicable, the self-similarity conditions should be fulfilled for the corresponding flow regimes in experiments.

When a stationary shock-wave discontinuity propagates through a material, the conservation laws of mass, momentum, and energy [2] are obeyed at its front. These laws relate the kinematic parameters, the shock wave velocity D and the mass material velocity u behind the shock front, with thermodynamic quantities — the specific internal energy E,

the pressure p, and the specific volume V:

$$\frac{V}{V_0} = \frac{D-u}{D}\,, \quad p = p_0 + \frac{Du}{V_0}\,, \qquad E - E_0 = \frac{1}{2}\,(p+p_0)(V_0 - V)\,, \tag{1}$$

where the subscript 0 indicates the parameters of the immobile material ahead of the shock front.

These equations permit determining the hydro- and thermodynamic characteristics of a shock-compressed material upon recording any two of the five parameters E, p, V, D, and u, which characterize the shock discontinuity. Determined most easily and precisely by standard techniques is the shock velocity D. The choice of the second recorded parameter depends on specific experimental conditions. This is ordinarily the mass velocity u of the shock discontinuity [2, 3] or the shock-compressed plasma density $\rho = V^{-1}$ [10].

An analysis of the inaccuracies of relation (1) shows that it is expedient, in the case of strongly compressible ('gaseous') media, to record the shock-compressed material density as the second parameter. At present, a technique for these measurements has been elaborated, which involves measurements of soft X-ray radiation absorption by cesium, argon, and air plasmas [4]. For lower-compressibility materials (condensed media), acceptable accuracy is afforded by recording the velocity of mass motion u. In this way, the states of degenerate metal plasmas and the dense Boltzmann plasmas of argon and xenon were investigated [2–4, 9].

In experiments involving determination of isentropic expansion curves for a shock-compressed material, the states in the centered dumping wave are described by Riemann integrals [2]:

$$V = V_{\mathrm{H}} + \int_p^{p_{\mathrm{H}}} \left(\frac{\mathrm{d}u}{\mathrm{d}p}\right)^2 \mathrm{d}p\,, \quad E = E_{\mathrm{H}} - \int_p^{p_{\mathrm{H}}} p\left(\frac{\mathrm{d}u}{\mathrm{d}p}\right)^2 \mathrm{d}p\,, \tag{2}$$

which are calculated along the measured isentrope $p_s = p_s(u)$.

By making measurements for different initial conditions and intensities of shock and rarefaction waves, it is possible to determine the caloric equation of state $E = E(p, V)$ in the $p - V$ diagram region spanned by the Hugoniot H and/or Poisson S adiabats. In experiments in dynamic action on the plasma performed to date, the shock intensities have been varied by varying the power of excitation sources — by varying the pusher gas pressure, the types of explosives, and launching devices. Furthermore, the initial state parameters were varied in various ways: by changing the initial temperatures and densities (rare gas, cesium, and liquid), or by using finely dispersed targets to enhance the effects of irreversibility [2, 3].

Therefore, dynamic diagnostic techniques, which are based on the general conservation laws, permit reducing the problem of the caloric equation of state $E = E(p, V)$ determination to the measurement of the kinematic parameters of motion of shock waves and contact surfaces, i.e. to recording distances and time intervals, which may be done with a high accuracy.

However, the internal energy E is not a thermodynamic potential with respect to the variables p and V, and to construct the closed thermodynamics of a system requires, in addition, the dependence of the temperature $T(p, V)$ on the state parameters. In optically transparent and isotropic media (gases, ionic crystals), the temperature can be measured simultaneously with other parameters of the shock compression. However, the majority of condensed media are, as a rule, opaque, so that the optical radiation of a shock-compressed medium is not observable.

The thermodynamically complete equation of state may be constructed directly from the data obtained in the dynamic measurements, without introducing *a priori* assumptions about the properties and nature of the material under investigation [10] employing the Fermi method, based on the first law of thermodynamics and the dependence $E = E(p, V)$ known from experiments (for more details, see Refs [4, 10]). This technique employed in dynamic experiments to construct the thermodynamically complete equation of state is free from any limiting assumptions as to the properties, nature, or phase composition of the material under study, because it relies on the most general conservation laws (1) and the first law of thermodynamics. In this case, the stationarity and one-dimensionality conditions should be fulfilled for the flow of the shock-compressed medium in order for the conservation laws to be usable in simple algebraic (1) or integral (2) forms.

It is significant that the shock wave not only compresses, but also heats the material to high temperatures, which is especially important for producing plasma — an ionized state of matter. Nowadays, a variety of dynamic techniques are employed in the experimental study of a strongly nonideal plasma (see Fig. 5).

The shock compression of an initially solid or liquid substance enables obtaining, behind the shock front, the states (of Hugoniot adiabat H, see Fig. 5) of nonideal degenerate (the Fermi statistics) and classical (the Boltzmann statistics) plasmas compressed to maximum pressures of ~ 4 Gbar and temperatures of $\sim 10^7$ K [11, 7]. At these parameters, the specific density of internal plasma energy is comparable to the nuclear energy density and the temperatures approach the conditions whereby the energy and pressure of equilibrium radiation begin to play a significant part in the total thermodynamics of these exotic states.

To reduce the irreversible heating effects, it is expedient to compress a material by a sequence of incident and reflected shock waves [12–16]. As a result, this multistage compression H_k becomes closer to the 'softer' isentropic compression (S_1), making it possible to obtain substantially higher compression ratios (10–50 times) and lower temperatures (~ 10 times) in comparison with a single-stage shock-wave compression. Multiple shock compression was used validly for the experimental study of pressure-induced plasma ionization [12–14] and substance dielectrization [16] at megabar pressures. Quasiadiabatic compression was also realized in the highly symmetric cylindrical explosive compression of hydrogen and rare gases [14]. In experiments involving 'soft' adiabatic plasma compression, in Refs [17, 18] advantage was taken of the explosive compression of samples by megagauss magnetic fields.

In another limiting case, when obtaining a high-temperature plasma is required, it is possible to effect the shock compression of lower (in comparison with solid) density targets — porous metals H_{m} [2–4, 19] or aerogels [20] — curve H_{a} in Fig. 5. This provides a way to sharply strengthen the irreversibility effects of shock compression and thereby increase the entropy and temperature of the compressed state.

The shock compression of rare gases and saturated alkali metal vapor by incident H_1 and reflected H_2 shock waves

allows studying the Boltzmann plasma in the domain with a developed thermal ionization [4, 10, 21–25].

The adiabatic expansion of a substance (curves S in Fig. 5) precompressed to megabar pressures by a shock wave permits investigating an interesting plasma parameter domain located between a solid and a gas, including the metal – dielectric transition region and the high-temperature portion of the boiling curve of metals with their critical point [4, 9, 26, 27].

Since the metallic bond energy is rather high, the parameters of the critical points of metals are extremely high (4.5 kbar and 8000 K for Al, 15 kbar and 21000 K for W) and unattainable for static experimental techniques. That is why until recently the critical point characteristics were measured only for three of all metals, which account for $\sim 80\%$ of the elements of the Periodic Table [4]. On the other hand, because the critical temperatures of metals are high and are comparable to their ionization potentials, metals in a near-critical state vaporize directly to an ionized state and not to a gas, as is the case in the rest of the chemical elements.

This circumstance may lead to exotic 'plasma' phase transitions predicted for metallization by Ya B Zel'dovich and L D Landau [28] and other theorists for strongly compressed Coulomb systems (see Refs [29, 30 – 33] and references therein).

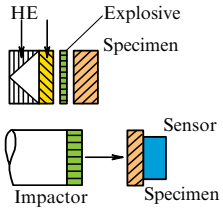
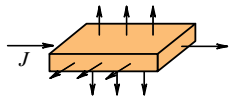
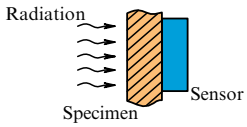
The experimental quest for these exotic plasma phase transitions today is among the most interesting problems of dynamic physics of high energy densities. The sharp rise (by five orders of magnitude) in conductivity [12 – 14, 25, 34, 35] and changing of the adiabatic compressibility [36, 37] discovered recently for nonideal hydrogen and deuterium plasmas, which was supported out by quantum-mechanical calculations by the Monte-Carlo technique [33], supposedly testifies to the experimental discovery of this plasma phase transition.

5. Drivers for intense shock waves

Today, a wide variety of ways of generating intense shock waves is employed in dynamic experiments. These are chemical, nuclear, and electric explosions; pneumatic, gunpowder, and electrodynamic guns; concentrated laser and soft X-ray radiation; and relativistic electron and ion beams [3, 4, 7 – 9] (see Table 1).

The first experiments involving the dynamic generation of a dense plasma and the measurement of its equation of state and conductivity were carried out on a pneumatic shock tube

Table 1. Schemes for intense shock generation

Explosive devices, guns Plane-wave lenses Acceleration of flyer plates Cumulation Single-stage guns Powder guns Two-stage guns Railotrons	
Electric explosion Cylinders Foils } + shell	
Radiation Laser radiation Electron beams Ion beams Soft X-rays Nuclear explosions	

and facilities for adiabatic compression [24, 10]. To provide a high density of saturated cesium vapor (for its subsequent compression), the experimental devices were heated to a high initial temperature of $\sim 900\,^{\circ}$C. These high heating temperatures (the device is red-hot) and a substantial chemical aggressivity of cesium made the experiments with nonideal cesium plasmas extremely difficult and costly.

The majority of subsequent dynamic nonideal-plasma experiments were performed using condensed chemical explosives (HE) as the energy source, because they possess a high specific energy capacity, which exceeds that of electric capacitors by six orders of magnitude.

In explosion plasma generators made on this principle, the shock wave in precompressed gases is excited by the expanding detonation products of condensed explosives, which fulfill the function of a piston [23]. These explosion shock tubes were employed for the experimental study of the equation of state, the low-frequency electric and Hall conductivities, the fast-ion stopping power, and the optical properties of a strongly nonideal plasma compressed to pressures of ~ 200 kbar [4, 21, 23, 42 – 44].

Substantially higher pressures of ~ 1 Mbar in gases and ~ 5 Mbar in metals were realized in so-called explosion guns (Fig. 6a) [3, 4, 8, 9, 19]. In these devices, a high-speed impact of metal strikers accelerated by detonation products to velocities of 5 – 14 km s^{-1} excites in a target a plane shock wave or a series of reverberating shock waves. The geome-

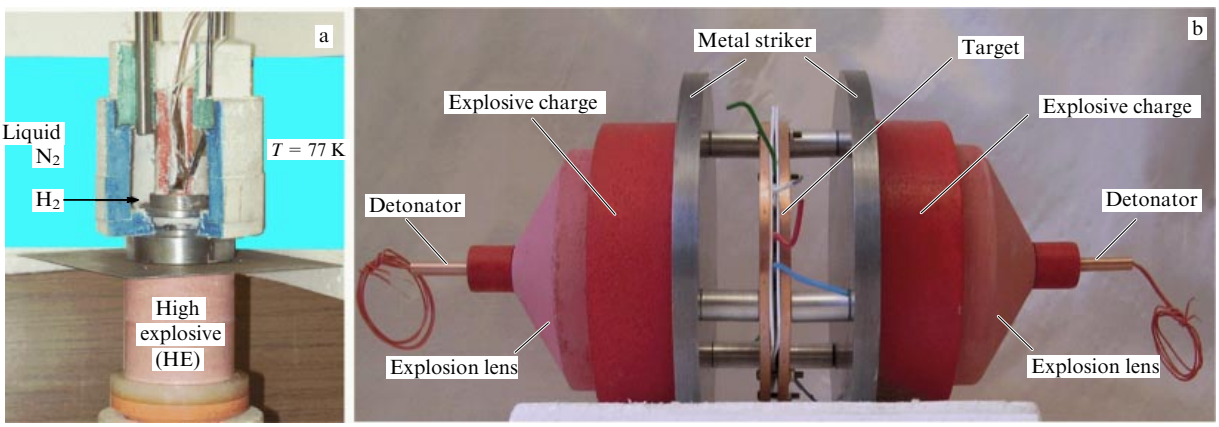


Figure 6. (a) Explosion generator for shock-wave plasma compression [13, 19]. (b) Explosion generator of counter-propagating shock waves [15, 16].

trical parameters of these experimental devices are selected in such a way as to eliminate the distorting effect of side and rear dumping waves to ensure the one-dimensionality and stationarity of gas dynamic flow in the region of recording the plasma parameters required for the application of the conservation laws in the self-similar form (1).

Interestingly, the kinetic energy of a metal striker moving at a speed of 10 km s^{-1} is close [34] to the kinetic energy of a proton beam in the cyclotron accelerator of the Fermi lab. And so the high kinetic energy of metal strikers in shock experiments produces a strongly compressed plasma just as a relativistic ion collision energy, which produces a quark–gluon plasma with enormous energy densities.

To increase the parameters of shock compression, in several experiments use was made of explosion generators of counter-propagating shock waves (Fig. 6b), where the material under investigation was loaded on both sides by the synchronous impact of steel strikers symmetrically accelerated by explosive charges [15, 16].

To increase the velocity of the throwing and hence the shock-compressed plasma pressure, advantage is taken of highly sophisticated gas-dynamic techniques. The technique of 'gradient' cumulation (Fig. 7, [38, 14]) proposed by Academician E I Zababakhin relies on a successive increase in the velocity of strikers in planar alternating heavy and light material layers. This technique is not related to the effects of geometrical energy focusing and therefore possesses a higher stability of acceleration and compression in comparison with the spherical one. The thus made explosion three-stage 'layer cakes' [19] accelerated a one-hundred-micrometer striker to velocities of 13–14 km s^{-1} and were employed to study the equation of state and the adiabatic expansion of nonideal metal plasmas.

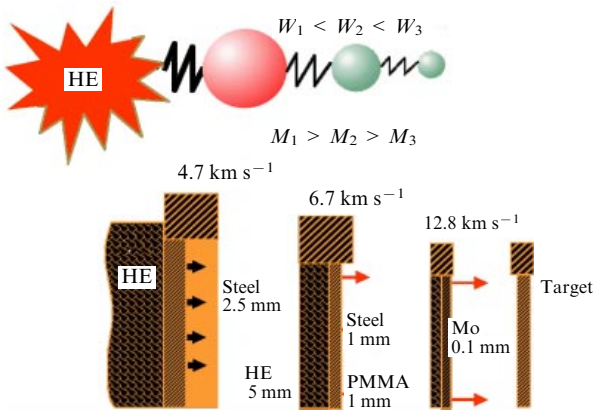


Figure 7. Principle of 'gradient' cumulation [38] and three-stage explosion 'layer cake' [14]. PMMA denotes polymethylmethacrylate.

Precision spherical explosion generators of intense shock waves (Fig. 8a) were designed in the USSR [3, 35, 39, 40] for the study of thermodynamic material properties at pressures ranging up to $\sim$ 10 Mbar. Using the geometrical cumulation effects in the centripetal motion (implosion) of detonation products and hemispherical shells, in devices weighing $\sim$ 100 kg with an energy release of $\sim$ 300 MJ it was possible to accelerate metal strikers to velocities of $\sim$ 23 km s^{-1}.

In higher-stability conical explosion generators, use was made of cumulation effects in the irregular (Mach) convergence of cylindrical shock waves (Fig. 8b) [41]. The combination of irregular cylindrical and 'gradient' cumulation effects enabled exciting in copper a shock wave with an amplitude of $\sim$ 20 Mbar, which is comparable to pressures in the near zone of a nuclear explosion [7].

Cylindrical explosion cumulation systems (Fig. 9a) are intended for effecting quasiadiabatic compression of H_2, D_2, and rare gases to megabar pressures by way of multi-stage wave reverberation between the heavy metal shell surface accelerated by detonation products and the symmetry axis of a cylindrical plasma volume. In this way, measurements were made of the conductivity, temperature, light absorption coefficient, density, and equation of state of a strongly nonideal plasma. Using this cylindrical devices pressure-induced metallization was detected, and the plasma phase transition was observed for the first time [36, 37].

To ensure the adiabaticity of dynamic compression in experiments [17, 18], the hydrogen plasma was compressed in cylindrical geometry by a megagauss magnetic field compressed, in turn, by an external metal liner accelerated by the detonation products of a condensed explosive.

To carry out experiments involving the interaction of an axial magnetic field with shock-compressed plasmas, explosion shock tubes (Fig. 9b) were developed, which were equipped with an external solenoid and a system for the electrocontact measurement of Hall currents [44] and low-frequency conductivity [4, 23].

In recent years, along with explosion techniques of shock generation, other methods have been increasingly used for pulsed energy cumulation. The corresponding facilities

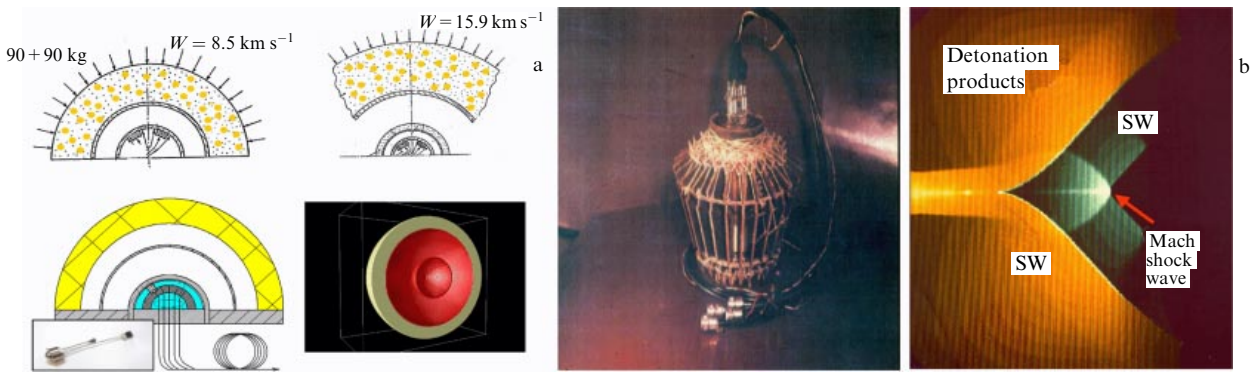


Figure 8. (a) Explosion spherical generators of intense shock waves [39, 9]. (b) Explosion conic generators of Mach shock waves [14] (shown on the right are the results of two-dimensional hydrodynamic simulations).

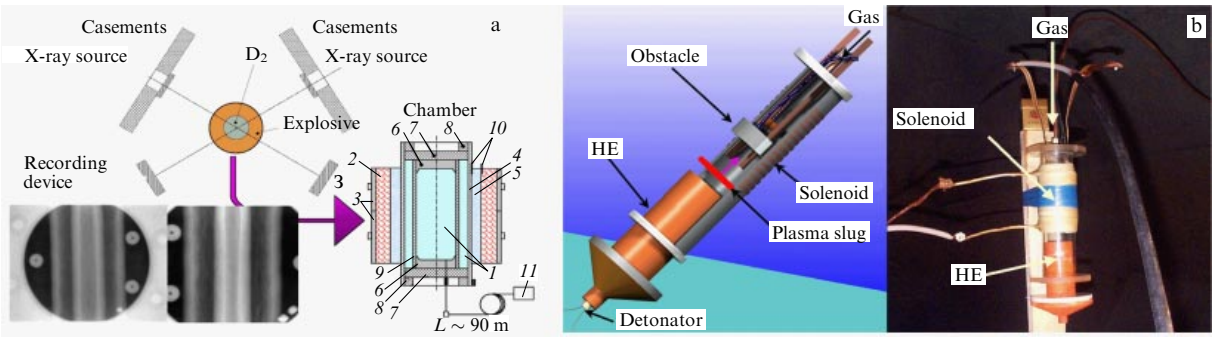


Figure 9. (a) Explosion cylindrical devices for quasiadiabatic plasma compression [36, 37, 42]. 1 — gaseous deuterium, 2 — explosive block, 3 — focusing system, 4 — external shell, 5 — plexiglass, 6 — inserts, 7 — blind flanges, 8 – screw nut, 9 — inner shell, 10 — contacts, 11 — gas source. (b) Explosion shock tube for measuring the low-frequency and Hall conductivities [4, 21, 23, 44].

constructed for inertial confinement fusion and for military applications are being used to an increasing extent in purely physical experiments. As a result of 'detente' and changes in defense priorities, costly and complicated high-power devices have become accessible to high energy density physics: high-power lasers, high-current Z-pinches and soft X-ray radiation sources, magnetodynamic guns, and electric-detonation systems, as well as high-intensity relativistic electron and ion beams. The advent of this technical equipment has greatly enhanced the experimental capabilities of generating and studying the physical processes at high and ultrahigh energy densities [5, 6].

To study the physics of a high-speed impact and the dynamics of intense shock waves, use was made of a railgun accelerator of condensed media [45]. In this electrodynamic gun, solid plastic projectiles were accelerated to velocities of $\sim 8-11$ km s^{-1} by a plasma arc with a pulsed current of ~ 1 MA. This method of acceleration is free from limitations that are inherent in gas-dynamic throwing methods and arise from the insufficiently high speed of sound in the pusher gas. However, the growth of plasma instabilities, strong electrode erosion, and other factors did not allow a significant increase in launching velocity.

Experiments with high-power relativistic e-beam generators (Fig. 10a) enabled obtaining strong shock waves in metal and plastic targets, as well as effecting the bulk heating of the plasma of low-density foam targets. In particular, when recording the dynamics of shock wave motion, an analysis was made of the effect of intrinsic magnetic fields of the beam on its absorption in the metal plasma [46].

Due to a substantially shorter (than for electrons) free path, intense beams of light and heavy ions turned out to be a more efficient instrument for the generation of high power densities in the plasma.

One of these pulsed devices — the KALIF high-current proton beam generator (Fig. 10b) delivers a specific power of $\sim 10^{12}$ W cm^{-2} at the target. This permits accelerating thin ($\sim 50-100$ μm) flyers to velocities of $\sim 12-14$ km s^{-1} and carrying out interesting measurements of the dense-plasma stopping power for fast protons with a kinetic energy of ~ 2 MeV, recording the thermodynamic parameters and viscosity of the shock-compressed plasma, and finding the spalling resistance of metals at ultrahigh rates of straining. One can see from Fig. 11 that the spalling resistance significantly rises (by $1-2$ orders of magnitude) with an increasing rate of straining to approach its theoretical limit, which is related to the propagation kinetics of dislocations and cracks in a pulsed stress field [8, 47].

The relativistic heavy-ion accelerators constructed for high-energy physics experiments (Fig. 12a) turned out to be

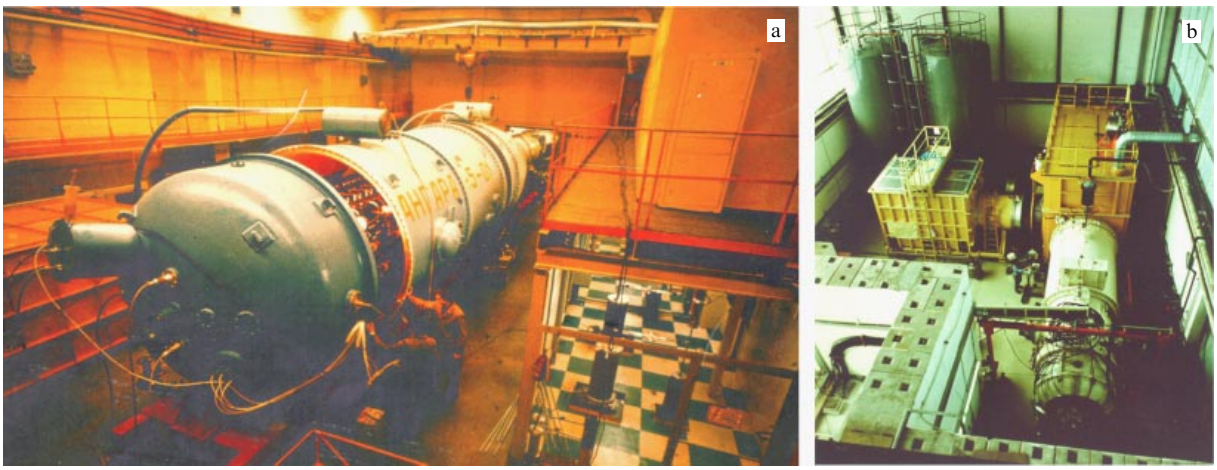


Figure 10. (a) ANGARA high-current e-beam pulse generator [46]. (b) KALIF high-power proton beam generator [47], proton energy ~ 2 MeV, current ~ 400 kA, power density $\sim 10^{12}$ W cm^{-3}.

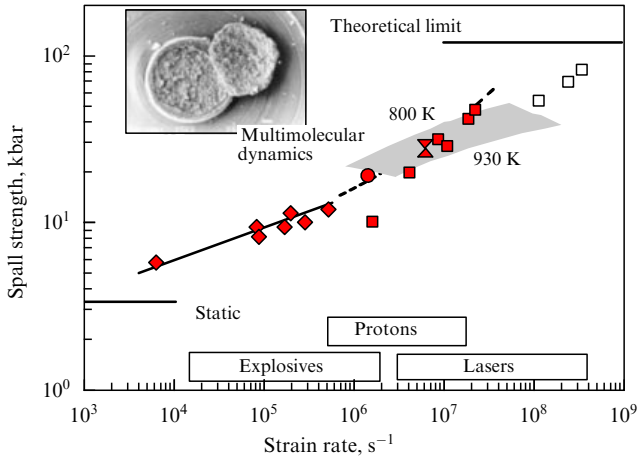


Figure 11. Spalling resistance of an aluminum – magnesium alloy at high rates of straining [8, 47].

candidates for controlled nuclear fusion with inertial plasma confinement and for experiments on the compression and heating of dense plasmas. Heavy-ion beams with a kinetic energy of 3 – 300 MeV nucleon^{-1} were employed in experiments on the heating of condensed and porous targets, the measurement of plasma stopping power for ions, and the interaction of charged beams with shock-compressed plasma produced by miniexplosion driven shock tubes [48].

Fast electric generators of high-power pulsed fluxes (Z, Sandia; Angara, Kurchatov Institute of Atomic Energy, etc.) were made for controlled nuclear fusion and for modeling the damaging action of nuclear explosions. They turned out to be highly useful as terawatt power sources for intense shock generation by high-intensity soft X-ray radiation in the Z-pinch geometry, and also as sources of pulsed megaampere currents for the electromagnetic acceleration of thin metallic liners to velocities of ~ 20 km s^{-1} [49] (Fig. 12b). In this case, by controlling the current parameters it is possible to effect a shock-less 'soft' compression of targets to a pressure of ~ 3 Mbar. By the laser-assisted recording of the parameters of quasi-isentropic compression, the states were determined to have lower temperatures than for shock-wave heating.

In experiments conducted at the Angara facility [50] (Fig. 12c), a pulsed ~ 4 MA current accelerated a plasma xenon liner to a velocity of ~ 500 km s^{-1}. The highly symmetric impact of this liner on the surface of a cylindrical porous target excited in it a thermal radiative wave, which emitted soft X-ray radiation with a temperature of ~ 100 eV. This high-intensity X-ray radiation emanating from the cylindrical cavity was employed for generating highly symmetric plane shock waves with an amplitude pressure of ~ 5 Mbar, exciting thermal radiative waves with a propagation velocity of ~ 100 km s^{-1}, as well as for accelerating metallic flyers to 10 – 12 km s^{-1}.

The highest power densities among laboratory devices were obtained by focusing laser radiation [4 – 6, 51 – 54]. A large number of costly and complicated laser systems (Fig. 13a) (NIF, Le Laser Mega Joul, Vulkan, OMEGA, GEKKO, and others) were made for problem of nuclear fusion with inertial hot-plasma confinement [5, 6]. This requires obtaining a thermonuclear plasma with extremely high energy densities — a temperature of ~ 10 keV, a density of ~ 100 g cm^{-1}, and a pressure of several gigabars.

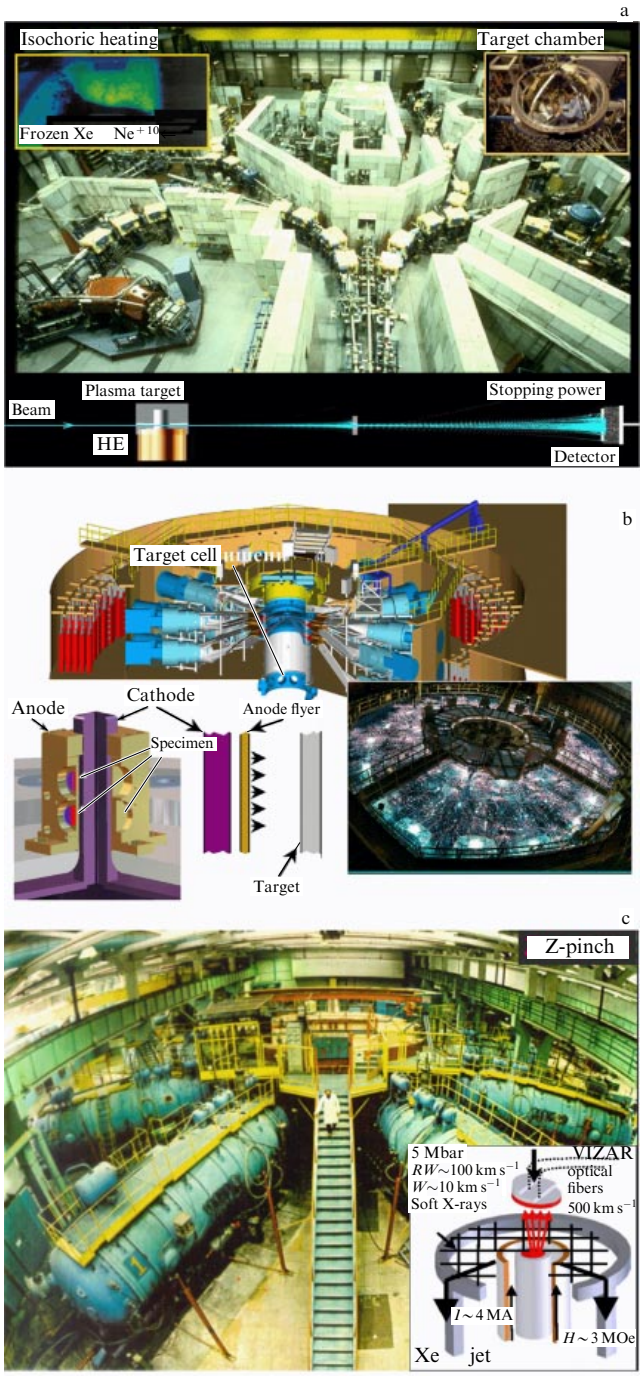


Figure 12. (a) Relativistic heavy-ion beam interaction experiments at the GSI accelerator [48]. (b) Schematic of electrodynamic acceleration of metal liners at a facility of the Sandia Laboratory, USA [49]. (c) ANGARA pulsed generator, TRINITI, intended for controlled nuclear fusion and experiments with shock and radiative waves [50].

Concurrently with the fusion program, also realized at these facilities is a wide-ranging program of research into the physical properties of matter and the physical processes in plasmas with extreme parameters [6, 51 – 56]. Active works are underway to study the equation of state and the reflection of laser radiation, to measure low- and high-frequency conductivities, to analyze the mechanical properties of materials at high rates of straining, to convert coherent laser radiation to soft X-rays, to analyze transient hydrodynamic effects, to study instabilities, and to model astrophysical plasmas (Fig. 13b [6]).

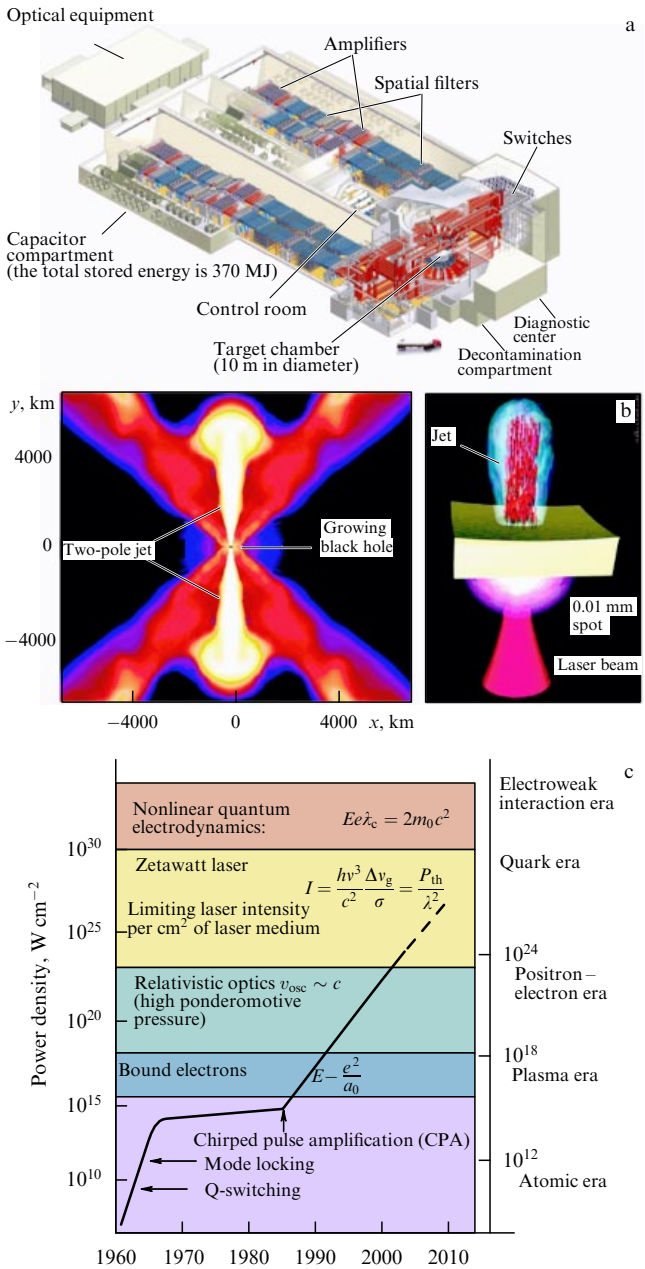


Figure 13. (a) NIF high-power laser system for controlled nuclear fusion and research in the area of high energy density physics [6]. (b) Laboratory astrophysics of high energy densities. Comparison of the model of a cosmic X-ray source and its laboratory modeling by way of a laser experiment [6]. (c) Buildup of laser power density and physical processes in laser-produced plasmas

Considerable progress in the experimental physics of high energy densities was related to the advent of tera- and petawatt laser systems [53], which enabled a sharp increase in intensity, up to record high intensities of 10^{22} – 10^{23} W cm^{-2}.

Several interesting and qualitatively new physical effects emerge in this power range (Fig. 13c [6]). Beginning with $q > 10^{14}$ W cm^{-2} (for $l = 1$ μm), the amplitude pressures of laser-generated shock waves enter the megabar range. Beginning from $W > 10^{17}$ W cm^{-2}, the electric intensity in the laser wave is comparable to the field intensity in the first Bohr orbit of hydrogen. From approximately the same

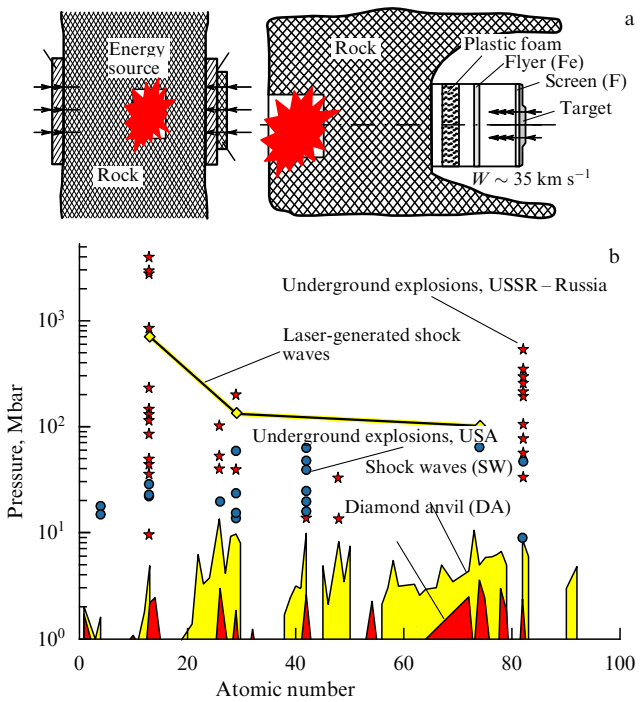


Figure 14. (a) Schematic of experiments in shock generation in the immediate vicinity of a nuclear explosion [7, 11]. (b) Typical pressures attainable in experiments.

intensities, in the absorption region there occurs an appreciable generation of nonthermal megaelectronvolt ions and electrons. Beginning with 10^{18} W cm^{-2}, the plasma electrons are accelerated to relativistic velocities in the electric field of the laser wave and the ponderomotive light pressure is comparable to the hydrodynamic pressure. For $J \sim 10^{21}$ W cm^{-2}, the light pressure is ~ 300 Gbar. For higher intensities ($\sim 10^{30}$ W cm^{-2}), the optical radiation energy density becomes sufficient for the breakdown of vacuum and spontaneous production of electron – positron pairs and then for the emergence of quark – gluon plasma. Further advancement along the laser intensity scale is limited by our imagination and knowledge of the structure of matter in the immediate spatio-temporal neighborhood of the Big Bang.

Since nuclear explosives exceed chemical ones by 6 – 7 orders of magnitude in specific energy capacity, the highest man-produced pressures in terrestrial conditions were produced precisely in underground nuclear explosions (Fig. 14a) [7, 11]. These costly and complicated experiments yielded a wealth of new and valuable information about the thermodynamic and optical properties of dense plasmas in the megabar – gigabar pressure range.

Figure 14b shows the pressures obtained now in laboratory and quasilaboratory conditions using the methods of shock generation described in the foregoing. The resultant data pertain to a wide range of nonideal plasma parameters, making it possible to estimate at ultrahigh pressures the validity range of the quasiclassical model of a substance — the Thomas – Fermi model [58]. It was determined that this model applies beginning with pressures of about 100 Mbar on the Hugoniot adiabat, while its validity range becomes substantially narrower with increasing temperature (the shock adiabats of porous materials).

6. Physical properties of matter under extreme conditions

The use of shock waves in plasma physics enabled gaining experimental information in a new and previously inaccessible range of condensed densities and megabar pressures. A strong collective interparticle interaction involving significant quantum effects is realized in these unusual states of matter.

Even the first experimental data on the thermodynamics of nonideal plasmas turned out to be rather nonpresumable and showed how unsound it is to extrapolate notions obtained for nonideal plasmas to the high-pressure range. It was determined [4, 24] that the pressure of a nonideal plasma at constant temperature and enthalpy was much higher than the pressure of an ideal plasma, whereas this pressure, according to the concepts developed at that time [2, 57], should have been lower than the ideal-gas pressure owing to the plasma polarization. A more detailed analysis revealed [4, 24, 57] that the unusual behavior of thermodynamic plasma properties was attributable to two physical effects: the increase in the number of free charges caused by a lowering of the ionization potential and additional repulsion of the particles arising from the compression-induced deformation of the discrete energy spectrum.

At the same time, much evidence on the shock compression of metals and rare gases demonstrates the 'oscillatory' nature of Hugoniot adiabats, which is caused by thermal ionization and pressure-induced ionization. This plasma compressibility lowering, which arises from the deformation of discrete atomic and ionic energy levels, is reliably recorded in experiments [4, 7, 14, 19].

Many theoretical nonideal-plasma models have been proposed to date to describe the shock-wave data in a broad domain of the phase diagram of matter. They are based on a superposition of plasma ionization models and cell models of a condensed state of matter [4, 14, 19, 22, 57].

Figure 15a illustrates the quality with which one of these theoretical models describes the thermodynamic states in the range of solid-state densities and high temperatures obtained by shock compression of porous nickel samples [19]. Interestingly, these experimental data correspond to the metal–dielectric transition region (Fig. 15b), where pressure-induced and temperature ionization effects are significant for the description of plasma thermodynamics [4, 19, 57].

The great body of thermodynamic data obtained to date reveals [3] (Fig. 16a) a pressure-induced 'smoothing' of the specific atomic volumes of chemical elements. Indeed, a sharp non-monotony of a volume V_0 of material per nucleus as a function of the nuclear charge Z, which is observed at normal conditions $P = 0$ (the lower curve in Fig. 16a), is a manifestation of the quantum nature of material structure. This is amply reflected in the structure of the Periodic Table and the chemical reactivity of the elements. The compression of materials is responsible for the 'crushing' and 'intermixing' of electron shells, so that the elements lose their chemical individuality and their behavior comes to be progressively more universal [58]. As indicated by experiment [3], with increasing pressure the observed oscillations become progressively less pronounced (curves $P = 1$ and $P = 10$ Mbar), thereby bearing out the idea of 'simplification' of the structure and properties of a material with its compression. This consideration substantiated the Thomas–Fermi model reliant on the quasiclassical approximation to the self-consistent field method [58]. The validity range of the

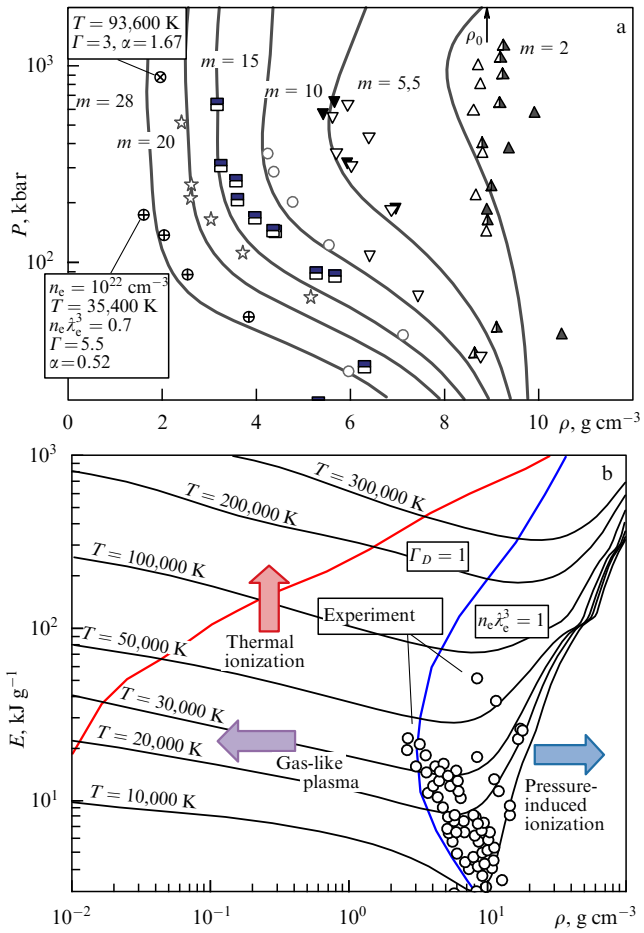


Figure 15. (a) Thermodynamics of nonideal nickel plasma [19]. Points — the results of shock compression of porous ($m \sim \rho_0/\rho_{00}$) specimens, α — the degree of ionization. (b) Energy density of the shock-compressed plasma of porous nickel [19].

quasiclassical model corresponds, to an order of magnitude, to ultrahigh pressures exceeding the characteristic value of the 'atomic' pressure $P > e^2/a_B^4 \sim 300$ Mbar ($a_B = \hbar^2/me^2$ is the Bohr radius). It seems likely that the comparison of this model with shock-wave measurement data made in Ref. [3] somewhat lowers the limit of applicability of the quasiclassical model to ~ 100 Mbar in Hugoniot adiabats.

The shock adiabat for Al [11, 7] shown in Fig. 16b shows the quality with which theoretical models describe the data on shock-wave plasma compression in a wide parameter range up to presently record pressures of ~ 4 Gbar obtained in the near zone of an underground nuclear explosion. Interestingly, the specific plasma energy at these ultrahigh pressures amounts to tremendous values of ~ 1 GJ cm^{-3}, which is close to the energy density of nuclear matter. In this compression regime, the pressure and energy of thermal radiation are comparable to P and T of kinetic electron and ion motion. It would supposedly make no sense to increase the shock compression pressure in experiments beyond these limits, because this situation would be dominated by the thermodynamics of the photon gas rather than the material itself.

Apart from metal plasmas, considerable interest is attracted to the investigations of shock-wave compression of a nonideal deuterium plasma, for which purpose use is made of lasers [54], the electrodynamic Z generator at the Sandia

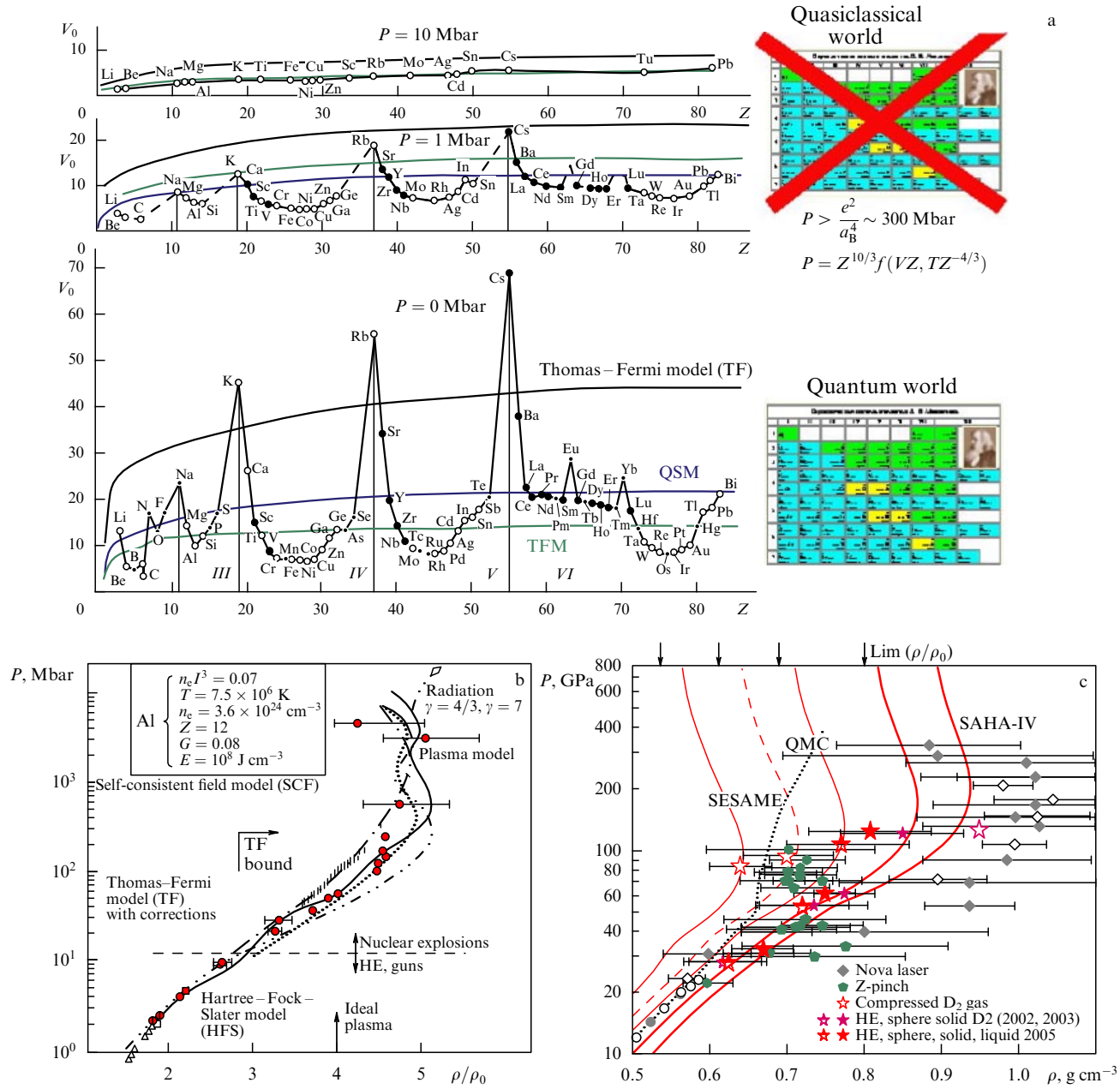


Figure 16. (a) Variation in atomic volumes of elements with increasing pressure [3]. (b) Shock-wave compression of aluminum to gigabar pressures [11, 7]. (c) Shock-wave compression of deuterium plasmas [49, 54, 59, 60]. QMC — calculations by a quantum Monte Carlo technique.

Lab [49], and spherical explosion devices [35, 59, 60] (Fig. 16c). Theoretical estimation show that the shock-compressed plasma in these experiments is strongly nonideal ($\Gamma > 1$) with developed ionization $n_e/n_D \sim 1$ and partial degeneracy $n_e \lambda_e^3 \sim 3$. One can see (Fig. 16c) that the models of nonideal plasmas [14, 19, 57] provide a reasonable description of the data on explosion and electrodynamic experiments involving the shock-wave compression of deuterium plasmas.

In recent years, as a result of the implementation of several international solar observational projects, there have emerged experimental data on the parameters of seismic waves and global oscillations of this star [61], which yields high precision experimental information (10^{-3}%!) about the thermodynamics of the hot multicomponent solar plasma. Figure 17a shows a comparison of these data with several theoretical nonideal-plasma models, which permitted defining more precisely the composition and role of bound states in the thermodynamics of a weakly nonideal multicomponent plasma.

The plasma conductivity provides valuable information about the elementary processes of charge transfer [57] and, most importantly, about the equilibrium plasma composition, because the transport current is directly defined by the 'free'-charge density. It is pertinent to note that distinguishing between free and bound charges is a nontrivial task for nonideal plasmas due to a strong interparticle interaction, which makes this differentiation somewhat ambiguous. By measuring the nonideal plasma conductivity, it is possible to judge the pressure-induced ionization — a dramatic manifestation of the interparticle interaction in compressed plasmas [4, 12 – 14, 30, 34, 42].

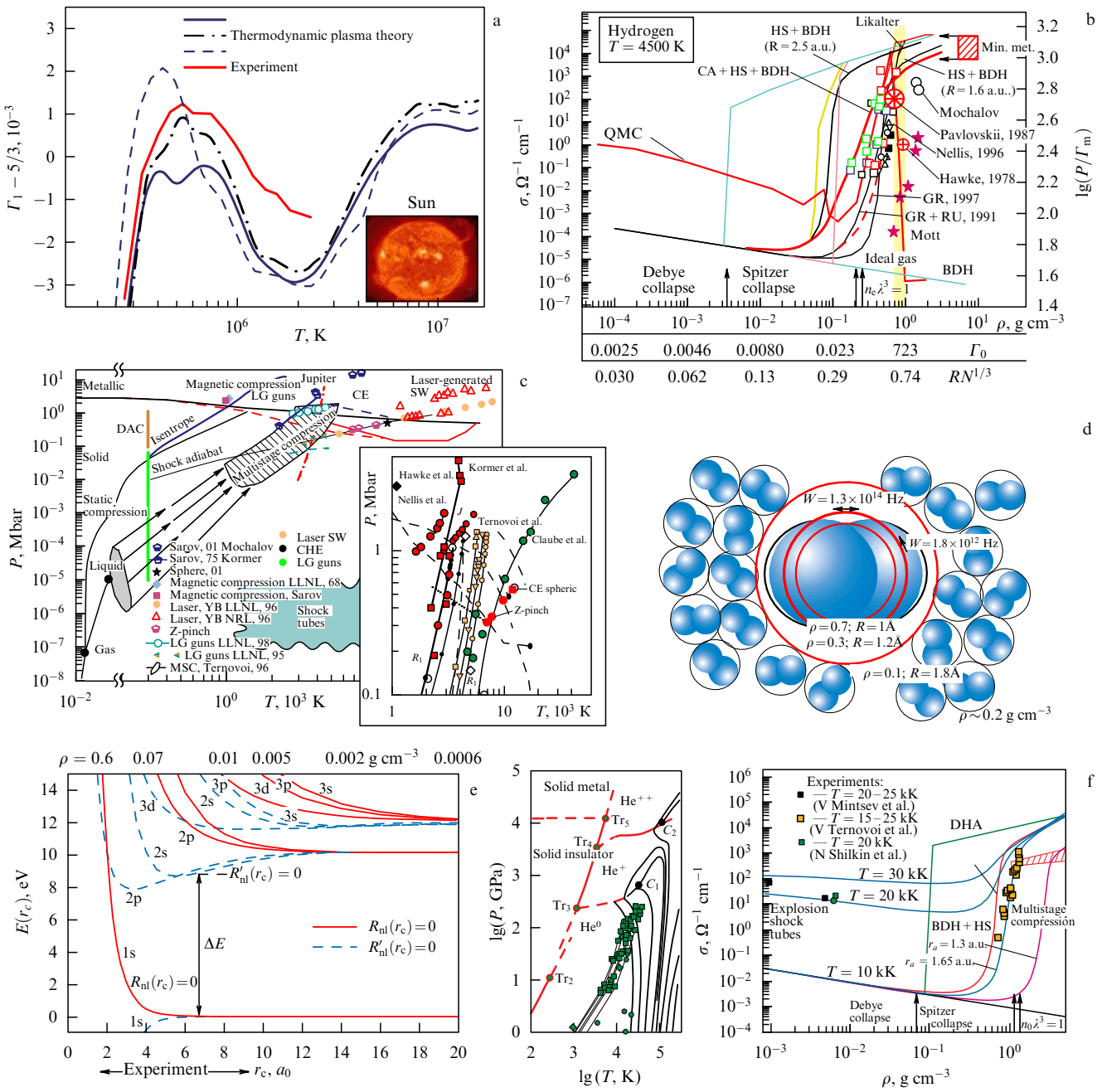


Figure 17. Solar 'seismology'. (a) Comparison of experimental data on the adiabatic compressibility index for the solar plasma and several theoretical plasma models [61]. Shown in the inset is a photograph of the Sun with prominences and bright energy release regions, which generate global oscillations and acoustic waves in the solar plasma. (b) Pressure-induced ionization of nonideal hydrogen plasmas [12, 13, 17, 18, 34–37]. The area of a thermodynamic phase transition is marked off, asterisks indicate the data of density measurements by pulsed X-ray radiography [36, 37], QMC — calculations by a quantum Monte Carlo technique [33, 63], DHA – Debye–Hückel approximation (in a small canonical ensemble), BDH — Debye approximation in a grand canonical ensemble, HS — hard sphere model, CA — confined atom model. (c) Hydrogen phase diagram. The boundaries of plasma phase transitions are indicated by dashed lines [14]. CHE — condensed high explosive, LG guns – light-gas guns, MSC — Multistage shock compression. (d) Hydrogen in the megabar pressure range [12, 13, 34–37]. Molecule — shaded circles (blue shaded in the electronic version of the paper), solid circles (red spheres in the electronic version) — boundaries (size) of the Wigner — Seitz cell at a density ρ. (e) Energy spectrum of compressed hydrogen as a function of the Wigner – Seitz cell size r_c. (f) Phase diagram and pressure-induced ionization of helium plasma.

It is well known that a material can be transformed into a conduction state (ionized) by way of either heating or compression [4, 57]. The temperature ionization is presently the principal and best-investigated mechanism in plasma physics [57]. It involves the heating of a tenuous plasma to a temperature comparable to the ionization potential of the material, $T \sim J$. An alternative to the thermal mechanism, pressure-induced ionization, involves a strong compression of a 'cold' material to densities $n \sim a_0^{-3}$ sufficient for the overlap of atomic orbitals, whose characteristic dimension is the Bohr radius $a_0 \sim a_B = \hbar^2/me^2$. To realize this criterion requires advancing to the condensed plasma density range and, as a consequence, generating pressures in the megabar range. For these two ionization mechanisms to be separated in experiment, one has to effect a 'cool' ($T \ll J$) compression of the material by weakening the thermal heating effects. Hydrogen

Table 2.

Year	Author and event
1766	Cavendish discovered a 'fire gas' — hydrogen
1898	Duval – liquid and solid (hydrogen) H_2 — an alkali metal?
1925	Fowler – stellar H_2 – plasma
1925	Hertzfeld – Clausius – Mossotti: dielectric catastrophe for 0.6 g cm^{-3}
1935	Wigner – Huntington: metallization at 2.5 Mbar, $T = 0$ K
1968	Ashcroft — high-temperature superconductivity of metallic hydrogen
1972	Kormer et al.: multistage explosive spherical compression to 4 Mbar
1978	Hawke et al. — explosive magnetic compression to 2 Mbar, 4000 K
1980	Mao – Hemley – Silvera – static compression to 1 Mbar
1987	Pavlovskii et al. — explosive magnetic compression to 1 Mbar, 3000 K
1990	Ashcroft — dissociation and metallization at 3 Mbar
1993	Nellis et al. — reverberation of shock waves — semiconductor properties, high conductivity
1996	Fortov, Ternovoi — explosive quasiadiabatic compression — nonideal plasma
1997	Da Silva, Cauble, et al. — laser-generated shock waves — nonideal plasma
2001	Trunin, Zhernokletov, Fortov, et al. — spherical explosive shock waves — nonideal plasma
2001	Assay, Knudsen — electrodynamic shock compression to 1 Mbar
2005	Zhernokletov, Mochalov, Fortov et al. — cylindrical explosive compression, plasma phase transition

proved to be the best-suited subject, because its small molecular weight leads to the lowest shock-compression temperatures.

Being the element of greatest abundance (90%) and at the same time the simplest element in nature, hydrogen has attracted the attention researchers of different specialties for almost 250 years. A brief chronology relating to the subject of our research is given in Table 2.

The vigorous study of the equation of state and conductivity is fostered by the significance of hydrogen plasma for astrophysics and the physics of giant planets, as well as by the quest for the high-temperature superconductivity of its metal phase. This has been a permanent pragmatic incentive of research over the last 50 years (Fig. 17c) [62].

Experiments aimed at studying the pressure-induced ionization of hydrogen and rare-gas plasmas were carried out with the use of a multistage shock compression technique, which permits effecting quasiadiabatic compression and thereby significantly (by a factor of ~ 10) increasing the compression factor and lowering (to $4-5 \times 10^3$ K) the substance temperature [12, 13, 34–37]. The experiments were conducted in plane and cylindrical geometries in light-gas guns and explosion launching devices, as well as cylindrical magnetic cumulation explosion generators [17, 18], which make use of an intense magnetic field to 'isentropize' the compression process.

Numerous experiments revealed a sharp increase (by 5–6 orders of magnitude) in static conductivity of hydrogen in a narrow condensed-density range at megabar pressures (Fig. 17b). In this case, the highest conductivity level attained in these conditions amounted to several hundred Ω^{-1} cm^{-1}, which is close to the conductivity of alkali metals and is not far from the 'minimal metallic' Ioffe – Regel conductivity [65]. That is why the effect under discussion is quite often referred to as 'metallization', which certainly is not quite correct: according to Refs [28, 65], the concepts of a metal and a dielectric may be separated only for $T = 0$. We believe that the case in point is 'pressure-induced ionization' [14, 30] caused by the overlap of the wave functions of neighboring atoms, which facilitates their ionization in a dense medium.

Figure 17d shows the geometrical characteristics of a hydrogen molecule in the isolated state as compared with the space available to one molecule (Wigner – Seitz cell radius) for a selected density ρ. One can see that the size of the hydrogen molecule for $\rho > 0.3$ g cm^{-3} becomes comparable to and then less than the Wigner – Seitz cell size. Physically, this corresponds to a strong overlap of the electron wave functions of neighboring atoms even in the ground energy state. This overlap creates favorable conditions for the delocalization [65] of electrons and their quasiunbounded motion in the plasma. The energy spectrum and effective ionization potential of hydrogen ΔE as functions of the Wigner – Seitz cell size are shown in Fig. 17e. Solid lines (red in the electronic version of the *Phys.-Usp.* journal) indicate the upper band edge calculated assuming that the radial part of the wave function is equal to zero at the cell boundary, $R_{\rm nl}(r_{\rm c}) = 0$. The lower band edge (in blue in the electronic version, dashed lines in Fig. 17e) was determined from a similar condition for its derivative, $R'_{\rm nl}(r) = 0$ (for more details, see Ref. [14]). One can see that in the course of compression with decreasing $r_{\rm c}$ in experiment there occur broadening of the energy levels, their transformation to energy bands, and, as a consequence, a decrease in the effective material ionization potential ΔE. The thus obtained quantity ΔE is in reasonable agreement with the corresponding value that follows from experimental measurements of the temperature dependence of the conductivity.

Similar conductivity measurement data for quasiadiabatically compressed plasmas were obtained for several other elements — He (Fig. 17f), D_2, Ar, Xe, and a hydrogen – helium mixture — the plasma of the Jovian atmosphere [14].

To additionally study the effect of electron shell overlap, experiments were staged [66] in the quasiadiabatic compression of the C_{60} fullerene, whose characteristic molecular size is far greater than the size of atomic hydrogen (7 Å versus 1 Å). As expected, the C_{60} fullerene 'metallization' pressure turned out (Fig. 18) to be approximately one order of magnitude lower than for hydrogen.

It is pertinent to note that the models of material transition to a conduction state introduced by Mott, Anderson, Lifshits, Hertzfeld, and Likalter (for more details, see Refs [14, 65]) also predict transitions in the parameter range close to those of the experiment.

A characteristic feature of the majority of physical nonideal plasma models is their thermodynamic instability in the strong-nonideality domain ($\Gamma > 1$) [28–33, 63, 64, 67–69], where experiments aimed at dynamic plasma compression [12, 13, 34–43] were planned and carried out. This instability of strongly compressed Coulomb systems corresponds to the 'plasma' phase transition predicted with simplified models by Wigner [29], Zel'dovich and Landau [28], Norman and Starostin [31], Ebeling et al. [30, 65], and Saumon and Chabrier [32, 68], as well as supported by molecular dynamics [69] and quantum Monte Carlo simulations [33, 61]. The corresponding plasma instability domain ('Debye collapse') predicted by the ring Debye approximation is indicated in Fig. 17b by the left vertical arrow. The nonideal hydrogen plasma simulations by the Monte Carlo method, which makes use of the Feynman path integral technique, are

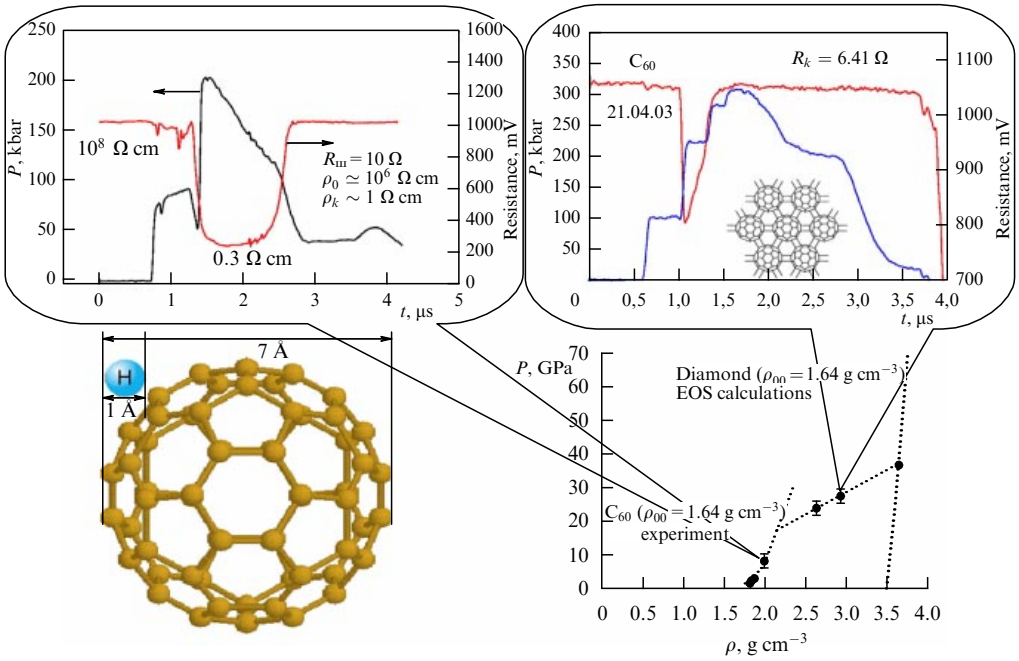


Figure 18. 'Metallization' of the C_{60} fullerene at high dynamic pressures [66].

outlined in Refs [33, 63]. One can clearly see from Fig. 17b the phase plasma stratification with the subsequent formation of an ordered plasma structure in the nonideal plasma.

Here, it is pertinent to note the general tendency of strongly compressed Coulomb systems to spatial ordering — a phase transition with the formation of plasma liquids and crystals. By now Coulomb crystals of this kind have been observed in several exotic experimental situations: in nonideal 'dust' [70] and colloid [71] plasmas, in ion bunches cooled by laser radiation in electrostatic traps [72] and cyclotron accelerators [73], and in the two-dimensional electron gas on the surface of liquid helium [74, 65].

With the aim of finding the phase transition in a real electroneutral electron-ion plasma, experiments were staged [36, 37] in explosive quasiadiabatic compression of deuterium plasma in cylindrical geometry involving plasma density measurements by the pulsed X-ray radiography technique (Fig. 9a). Experimental data (Fig. 19a) revealed a sharp plasma density jump ($\sim 25\%$) at a pressure of ~ 1.2 Mbar in precisely the parameter range where electrophysical measurements demonstrate a sharp rise in conductivity (by 5–6 orders of magnitude) (Fig. 17b and the data on conductivity in Fig. 19a) and where quantum Monte Carlo simulations [33, 63] lose their stability. The nonideality parameter estimated for these conditions is $\Gamma \sim \sim 150-200$ for a partial plasma degeneracy $n\hat{\lambda}^3 \sim 1$.

It is believed that the resultant thermodynamic and electrophysical measurement data are testimony to the experimental recording of a phase transition in a nonideal plasma subjected to multistage shock compression.

The shock compression [77] of 'simple' metals revealed an amazing and nontrivial behavior of degenerate strongly nonideal plasmas in the megabar pressure range [75–77]. According to the notions which had existed to that point, the electronic properties of alkali metals are described by the simplest model of a uniform electron Fermi gas with point-like ions residing inside of it. However, modern sophisticated quantum-mechanical models [75, 76] predict the formation of complex crystal structures with large coordination numbers at high pressures, in which 'pairing' of conduction electrons occurs and, as a consequence, there is a lowering of the conductivity in the 0.3–1.0 Mbar pressure range.

Experiments in the quasiadiabatic compression of Li, Na, and Ca performed in this dynamic pressure range [16, 77, 76] reliably demonstrated this unusual effect — the pressure-induced 'dielectrization' of simple metals [16, 77, 76] (Fig. 19b). One can see that the compression of these metals initially lowers their conductivity ('dielectrization') and then, beginning from 1.2–2 Mbar they return once again to the 'metallic' state, which would supposedly persist under further compression.

To study the 'temperature' ionization of dense plasmas, experiments were staged in the shock-wave compression of heavy rare gases, whose large molecular weight makes their shock-induced heating especially efficient. The 'Coulomb' contribution (caused by electron scattering from charges) of static plasma conductivity derived from the experiments is shown in Fig. 19c in the dimensionless form: $\sigma^* = \sigma_k/\omega_p$ (σ_k is the Coulomb contribution of the conductivity, $\omega_p = (4\pi e^2 n_e^2/m)^{1/2}$ is the Langmuir frequency). One can see that the experiments cover a wide parameter range, including the high-density (up to 3 g cm^{-3}) and substantial plasma nonideality ($\Gamma > 10$) domain. In this domain, the existing conduction models lead to absurd results (the Spitzer and Coulomb divergences) arising from the overestimation of the Coulomb scattering and screening in these models [4, 14, 42].

Subsequently, these conductivity measurements were supplemented with highly informative measurements of the Hall conductivity of shock-compressed plasma [78] in a longitudinal magnetic field, which permitted determining the carrier density as is customary in semiconductor physics [65] (Fig. 20a).

Measuring the resonance (for $\omega_{\text{laser}} \sim \omega_p$) laser radiation reflection from a shock-compressed plasma enables obtaining

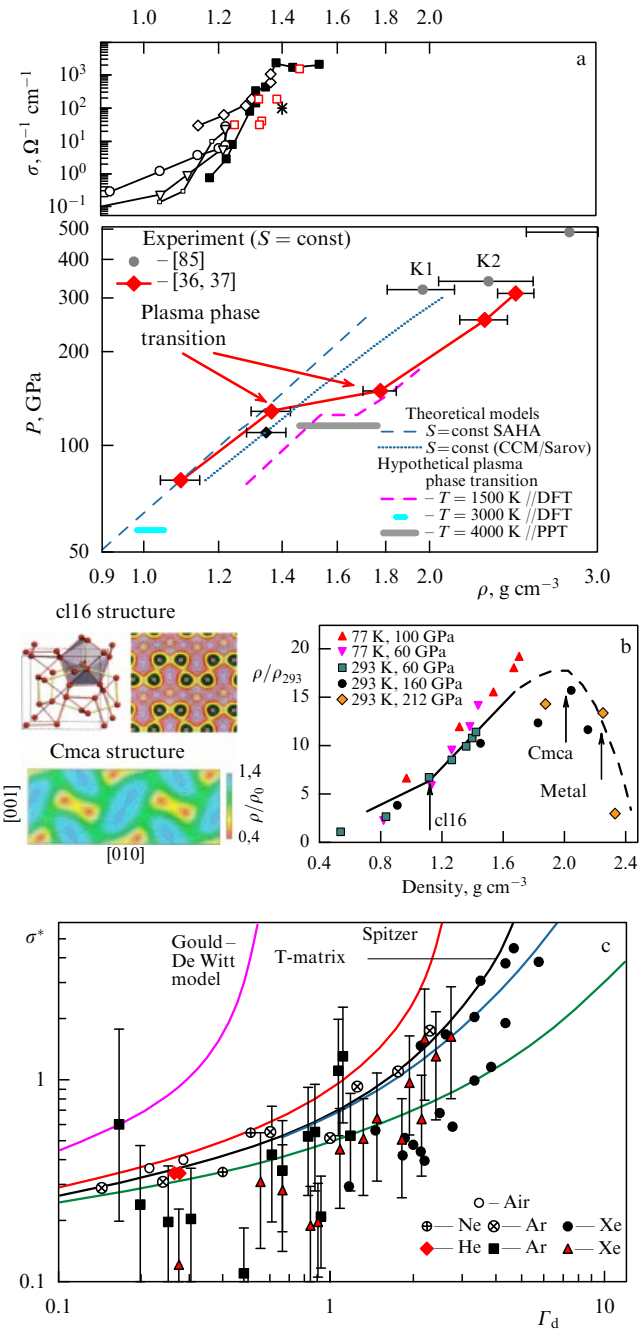


Figure 19. (a) Recording of the adiabatic compressibility of a deuterium plasma [36, 37]. The plasma phase transition domain is shaded (shown in yellow in the electronic version). The conductivity data are given above. (b) Pressure-induced 'dielectrization' of degenerate lithium plasma [16]. Shown on the left are the structure and electron density distribution of the high-pressure phase [75]. (c) Temperature ionization $T \sim J$. Static non-ideal-plasma conductivity [4, 14, 43, 78]. See Ref. [57] about the models.

independent information about the number of 'free' electrons and the electron collision frequency, thereby indirectly verifying the models of plasma ionization and scattering in a nonideal plasma. Referring to the data in Fig. 20b, the plasma reflectivity increases with density to attain high values characteristic of metallic mirrors.

Measurements of the optical properties of strongly compressed plasmas also yielded quite unexpected results. According to the notions elaborated for nonideal plasmas [57], increasing density should strengthen opacity due to the broadening of spectral lines and the shift of the bremsstrahlung continuum. However, experimental data have shown [4, 21] that in some cases the broadening effects are less pronounced, while the highly excited states themselves may be missing from the spectra observed (Fig. 20c). The matter is that strong interparticle interaction in nonideal plasmas is responsible for the shift, broadening, and 'solution' of spectral lines (Fig. 17e) as indicated by the observed emission spectra of hydrogen (Fig. 20c), argon (Fig. 20d), aluminum, and xenon plasmas. These subtle effects are partly described by a confined atom model [4, 14, 42].

In the context of this model [4, 14], the plasma are treated as an equilibrium mixture of electrons, ions, and neutrals. Their internal electronic structure was calculated by the quantum-mechanical Hartree – Fock technique, which permits calculating, subject to the corresponding boundary conditions, the wave functions and the energy levels (Figs 17e and 17f) and then the corresponding oscillator strengths of spectral lines and the cross sections for excitation and ionization [14, 81]. These calculations are exemplified for argon plasmas in Fig. 20d, which clearly shows the effect of 'forcing-out' of the energy levels responsible for its 'blooming' ('transparentization').

To study the physical properties of materials in a wide range of the phase diagram, method of adiabatic expansion, (see Refs [4, 19, 26, 27]), was proposed which relies on the production of high-energy states by the adiabatic expansion of a material preliminarily compressed and heated at the shock front to pressures ranging into the megabars (Fig. 21a). This method permits obtaining in dynamic experiments the states of a strongly nonideal plasma that are intermediate (Fig. 5) between a strongly compressed state and rarefied metal vapor, including the metal – dielectric transition region, which is extremely difficult to study, and the high-temperature portion of the boiling curve in the neighborhood of the critical points of metals. This experimental method enables us to continuously connect two extreme states of matter — condensed-density megabar-pressure nonideal plasmas and the low-temperature rarefied metal vapor domains. It is significant that in this way it is possible to investigate the otherwise inaccessible high-temperature portion of the boiling curve of metals up to their critical point [82], where the substance is highly ionized, stimulating the fast kinetics of phase transformations [26, 27]. Several experimental results on the adiabatic expansion of uranium are presented in Fig. 21a, where advantage was taken of the shock compression of a porous specimen to increase the entropy of the initial states prepared for the subsequent expansion. One can see that the lower portions of adiabats S_1 and S_4 enter the two-phase domain to give rise to jumps in adiabatic expansion velocity (the right-hand side of Fig. 21a).

Direct measurements of the effective glow temperature T_{ef} of an adiabatically expanding bismuth plasma yield information about the optical properties of nonideal plasmas [83]. The expansion from shock-compressed states for a pressure of ~ 3.6 Mbar corresponds to the realization of essentially supercritical bismuth plasma states, where the nonideality effects are not so significant and the observed temperature corresponds to an standard [57] calculation, which takes into account free – free (f – f) and bound – free (b–f) transitions. The expansion from lower pressure states ($p_H = 2.8$ Mbar) corresponds to trancritical states, where nonideality effects markedly affect the discrete energy spectrum and exclude it (as with experiments on the shock-

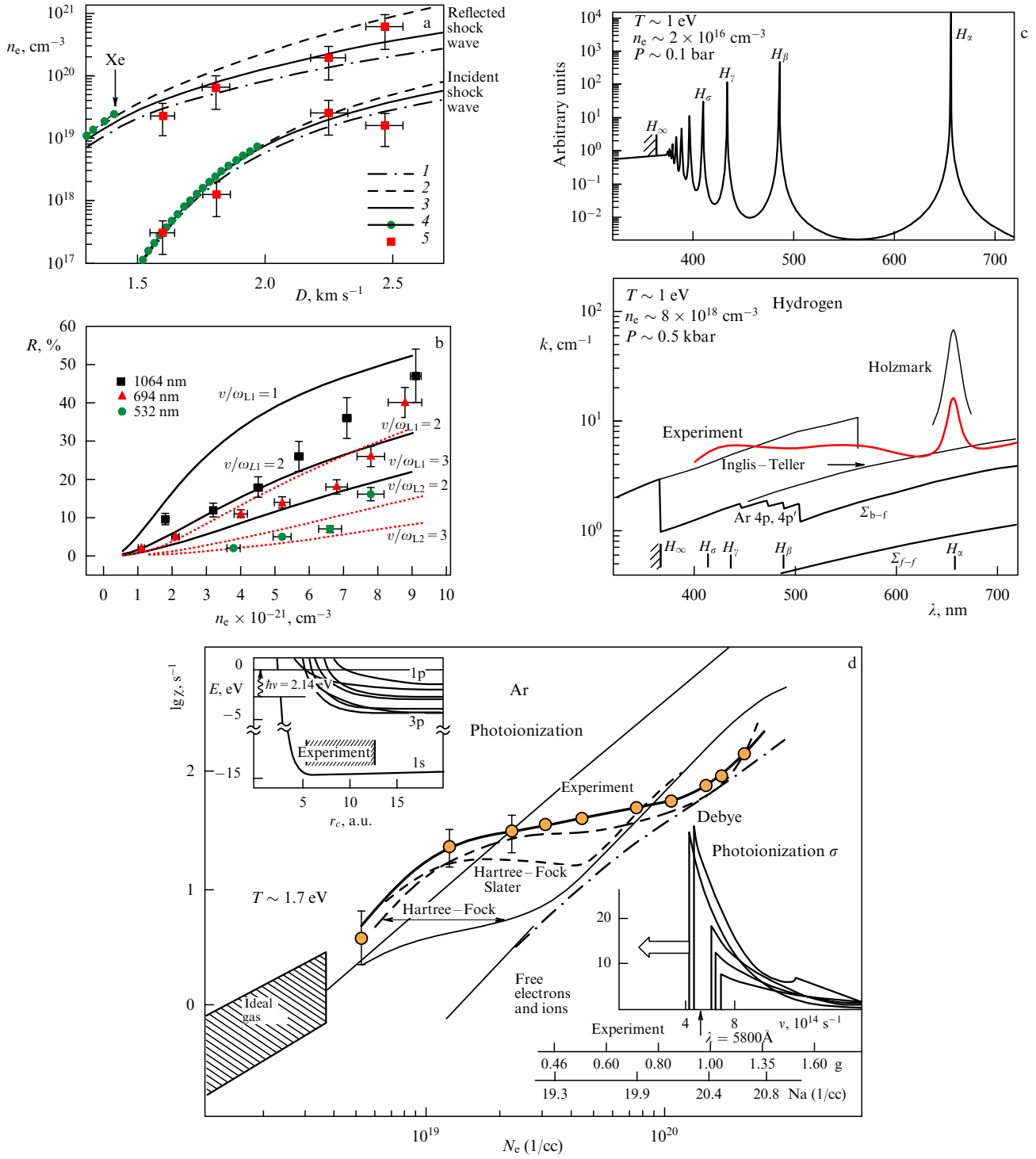


Figure 20. (a) Electron density of xenon plasma derived from Hall conductivity measurement data [78]. (b) Coefficients of reflection from the shock-compressed plasma front for laser radiation with a frequency n [79]. (c) Effect of spectral line 'solution' in a nonideal hydrogen plasma [21]. Low-density plasma spectrum ($n_e \sim 2 \times 10^{16}$ cm^{-3}). Spectrum of a shock-compressed nonideal plasma with $n_e \sim 8 \times 19^{18}$ cm^{-3}. (d) Optical properties of the compressed argon plasma – plasma bleaching effect [21].

compressed plasma of H_2 (Fig. 20c), Ar (Fig. 20d), Xe, and Al) from photoabsorption.

A characteristic feature of the high-temperature evaporation of metals and their oxides consists in the fact that in the trancritical region these materials vaporize directly to the plasma phase rather than the unionized vapor state, as happens with the majority of other materials [82]. This leads to several interesting phenomena like the fast kinetics of evaporation and condensation [26, 27] or 'incongruent' phase transitions caused by ionization and plasma nonideality [84].

The experimental data (Figs 21a and 21b) obtained via the dynamic technique of adiabatic expansion were employed for constructing semiempirical wide-range material equations of state [85]. Having been derived for the numerical simulation of high-energy processes and for engineering calculations,

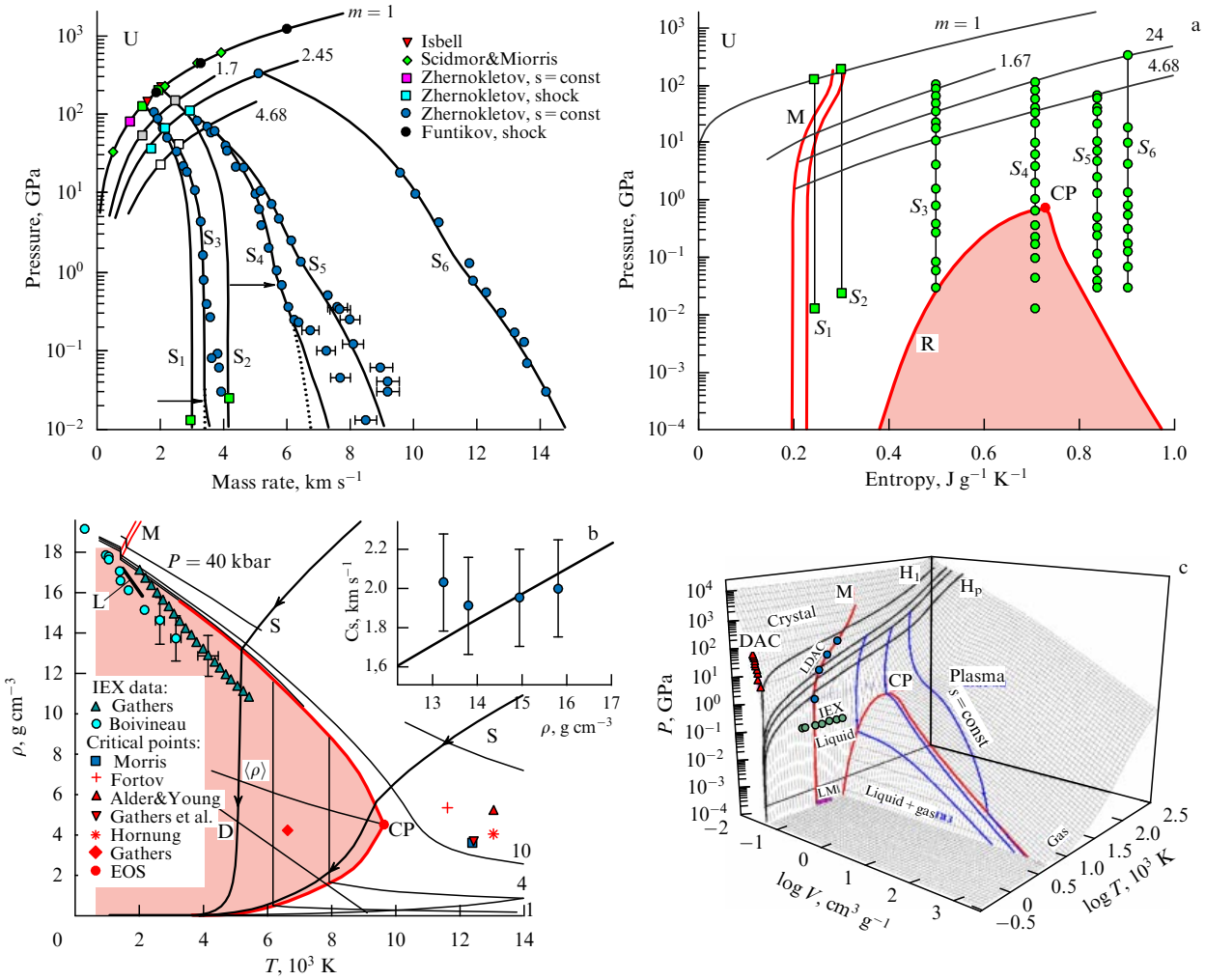


Figure 21. (a) Adiabatic expansion of shock-compressed uranium plasma [80]. (b) High-temperature evaporation of uranium in the trancritical region [80, 85]. (c) Semiempirical equation of state of uranium [85].

these equations of state provide a consistent description of all four (solid, liquid, gas, and plasma) states of matter, reproduce the available data of static and dynamic experiments, and reproduce phase transitions (melting, evaporation, ionization, and polymorphism). In the ultrahigh-pressure and temperature domain, these equations of state exhibit correct asymptotics to a Thomas – Fermi ultrastrong-compressed substance and Debye – Hückel quasi-ideal plasma models.

Table 3. Source data for the construction of semiempirical wide-range equations of state.

Static experiments:	• isotherms $T = 293$ K • pressure in the melting curve • volumes and enthalpy in the melting • boiling temperature at $P = 1$ atm • binding energy • electron conductivity
Dynamic experiments:	• shock adiabats of a solid specimen • shock adiabats of a porous specimen • expansion adiabats • electric explosions of conductors • shock compression temperature • speed of sound in shock-compressed state
Theoretical asymptotics:	• Thomas – Fermi theory with quantum and exchange corrections • plasma ionization model • electronic spectrum at low temperatures

The information sources employed for the construction of semiempirical equations of state are collected in Table 3, and Fig. 21c shows the form of the corresponding thermodynamic surface.

7. Conclusion

The use of shock waves in plasma physics has made it possible to obtain in laboratory conditions states of matter with extremely high energy densities typical for of the first seconds of the expansion of the Universe after the Big Bang and the states typical for such astrophysical objects as stars, giant planets, and exoplanets.

The information gained in dynamic experiments substantially broadens our basic notions about the physical properties of matter in a vast domain of the phase diagram up to ultrahigh pressures, which exceed the atmospheric pressure by 10 orders of magnitude, and to temperatures exceeding the human body temperature by 7 orders of magnitude.

Naturally, this difference in scales is amazing. However, Voltaire advised us to remember that "...in nature this

phenomenon is perfectly natural and commonplace. The domains of some rulers in Germany and Italy, which can be circled in about a half hour, when compared with the empires of Turkey, Moscow, or China, give only a faint idea of the remarkable contrasts that are hidden in all of nature" [86].

We see that each time we break into a new domain of the state of matter the plasma properties we measure turn out to be highly unusual and, as a rule, in sharp contradiction with the notions and models elaborated earlier. And this is precisely what makes the advance along the plasma temperature and pressure axes an especially exciting and fascinating task.

Due to space limitations, in this paper I could touch upon only the research I myself participated in or upon closely related works. Substantially more information on the physics of nonideal plasmas may be obtained from the reviews and monographs cited here.

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