

100th ANNIVERSARY OF THE BIRTH OF Ya B ZELDOVICH

PACS numbers: **01.60.+q**, **62.50.–p**, **64.10.+h**, **64.30.–t**, **65.40.–b**

Ya B Zeldovich and equation of state problems for matter under extreme conditions

V E Fortov, I V Lomonosov

DOI: 10.3367/UFNe.0184.201403b.0231

Contents

Abstract. In the amazing range of Yakov Borisovich Zeldovich's research interests — from general problems of chemical physics, kinetics, combustion, detonation, and shock waves to elementary particles and cosmology — the physics of matter under extreme conditions occupies a special position. This paper reviews some of Ya B's work on shock waves and equations of state of matter. Among Ya B's basic ideas are the utilization of shock data to develop thermodynamically complete equations of state; the shock compression of porous matter, and the adiabatic expansion of shock-compressed materials. The widespread use and development of these ideas as tools for the present-day studies of extreme conditions are illustrated with examples.

1. Introduction

Some famous natural scientist, conceivably L D Landau, said that if a scientist and his work are remembered five years after his death, this is an outstanding scientist.

It has been 25 years since Yakov Borisovich Zeldovich passed away, but there is a feeling that he is somewhere around. Even today, his ideas, suggestions, and advices lay the foundation for modern research into combustion, detonation, the equations of state of matter, and the physical and chemical aspects of shock and detonation waves, i.e., the area which is referred to as the 'physics of extreme states of matter' [1–10], or the 'physics of high energy densities' [11].

Work in this area has long been pursued under different parameters, by different techniques, and at different facilities by people who never knew Yakov Borisovich but in essence are his third- and fourth-generation pupils: pupils, because they took up and are taking up the 'Bible' of shock waves — the remarkable monograph, *Fizika Udarnykh Voln i Vysokotemperaturnykh Gidrodinamicheskikh Yavlenii* (*Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*) [4], by Zel'dovich and Raizer — and because they are learning from Ya B's direct pupils and developing the novelties introduced by Ya B's work.

Shock and detonation waves [1, 2, 4] were, perhaps, the areas of Ya B's first and deepest devotion, and his path in science involved successive studies of explosive phenomena of growing intensity and of different physical natures — from chemical explosions to nuclear and cosmic-scale ones.

Ya B Zeldovich made basic contributions to many scientific areas. In his later years, he was entirely absorbed by cosmology, but he always felt 'special affection' for intense shock and detonation waves, calling this area 'evergreen', was well informed about current investigations, and collected materials for a new monograph on shock waves. He took a vivid and informal interest in the events occurring in this area of physics and followed the news, remaining highly professional in these problems.

Curiously, Ya B constructed his famous theory of combustion and detonation at precisely the right time — in the thirties, just before O Hahn and F W Strassmann discovered the neutron fission of uranium in 1939, which marked humanity's entry into the nuclear era. This is the reason why Academician Ya B Zeldovich will forever remain in the history of technical civilization as one of the brightest pioneers of that epoch.

V E Fortov Russian Academy of Sciences,
Leninskii prosp. 14, 119991 Moscow, Russian Federation
E-mail: fortov@ras.ru
I V Lomonosov Institute of Problems of Chemical Physics,
Russian Academy of Sciences,
ul. Akademika Semenova 1, 142432 Chernogolovka, Moscow region,
Russian Federation
E-mail: ivl143@ficp.ac.ru
Tomsk State University,
prosp. Lenina 36, 634050 Tomsk, Russian Federation

Received 22 November 2013, revised 23 December 2013
Uspekhi Fizicheskikh Nauk **184** (3) 231 – 245 (2014)
DOI: 10.3367/UFNr.0184.201403b.0231
Translated by E N Ragozin; edited by A Radzig

Ya B worked a lot and fruitfully, and expected the same from others. Discussions would end with a suggestion to put the finishing touches on something and bring the results tomorrow or the day after tomorrow. His responsible and obliging attitude for scientific business was amazing.

His review reports to symposia on combustion and explosion were up-to-date, impressive, profound, and oriented toward future prospects, not toward the work of days gone by, as is often the case with 'generals of science'. In doing this, Ya B would carefully prepare his speeches and reports, consult a wide circle of experts, look through the literature, and agitate his colleagues with new ideas and suggestions. He acutely felt his responsibility for the state of science on combustion and explosion in this country, tried his best to stimulate activity, and searched for new problems and approaches. Ya B set up and headed the influential and diversified Council on Combustion in the Academy of Sciences.

Ya B was one of the first to recognize the potentialities of pulsed lasers [12] and charged particle beams [13] for the generation of shock waves, and strongly recommended researchers to take it up. Today, this has evolved into one of the most impressive areas in high energy density physics, with a wealth of new and unexpected effects and applications. Ya B also promoted research on the physics of nonideal plasmas [14]: he believed that this field concealed many interesting and unexpected effects and that intense shock waves were the most suitable instrument for studying these states of matter, which are exotic on Earth but quite abundant in the cosmos [10]. He promptly recognized the capabilities of powerful computers and actively participated in the work on the numerical simulation of plasma dynamics, Rayleigh–Taylor instability, nonstationary phenomena in detonation, and the critical diameter of pinpoint blasting of condensed explosives. Here, his phenomenal intuition was inestimable.

Having begun his scientific work as a laboratory assistant, Ya B had a subtle perception of experiments; he worked a lot with experimentalists and did so with pleasure, and that work was highly fruitful for all of its participants. Having a great expertise in applied and engineering work, he fully realized the special character of the limitations of theoretical and experimental techniques and would say: "Theorists believe that experimental data are 100% trustworthy, and experimentalists regard a theoretical result to be the 100% truth. Neither the former nor the latter know that the reality is somewhere between."

When coming to our explosion facilities in Chernogolovka, quite often with his friends, Academicians N N Semenov and Yu B Khariton, Ya B would discuss for hours the arrangements and results of experiments, delve into seemingly minor details, and always suggest tricky approaches, which often broke the deadlock. And yet most important was his capability to interpret experimental data — quite often even without making estimates, owing to his surprising intuition and expertise in special problem-oriented research.

In the early 1970s, in the epoch of pulsed fusion growth, an idea emerged of utilizing conical targets for the quasi-spherical shock-wave compression of thermonuclear plasma. The idea seemed to be attractive. A large cooperation set up: the I V Kurchatov Institute of Atomic Energy (IAE) employed relativistic electron beams, the General Physics Institute of the USSR Academy of Sciences (GPI) employed lasers, the Branch of the Institute of Chemical Physics (BICP) in Chernogolovka used chemical explosives and the electric explosions of foils. The L D Landau Institute for Theoretical Physics took up the theory. The cooperation was promptly organized, without a wealth of papers, red tape, or formalism, which are typical for our time. Even the first shots yielded $10^3 - 10^7$ thermonuclear DD neutrons.

The higher-ups arrived — N N Semenov, A M Prokhorov, Yu B Khariton — and one more check was made to confirm the detection of neutrons. An interesting avenue of applications emerged, which was due to a favorable scaling in target size. Ya B attentively familiarized himself with the data obtained and suggested several new arrangements of the experiment, which showed the decisive role of cumulative effects violating the scaling but describing surprisingly well virtually all experimental data.

When working on this problem, he urged the more extensive application of chemical explosive techniques for producing hot plasmas, both thermonuclear and nonideal. Incidentally, a similar explosive thermonuclear idea, in combination with electrodynamic preheating, has unexpectedly come under development and is showing good promise [15].

Ya B also gave a start in life to other lines of research involving the use of shock waves in nonideal plasma physics. His basic contribution to dynamic high-pressure physics is well known: Ya B and his colleagues (L V Al'tshuler, S B Kormer, V V Krupnikov, A A Bakanova) carried out pioneering experiments on the shock-wave compression of substances to megabar pressures. These experiments were so far ahead of their time that their American counterparts, who were unaware of the experimental details, believed that these ultrahigh pressures had been obtained in the collision of ballistic rockets in terrestrial orbit. This remarkable work of the 1960s related to metals and dielectrics, while plasma states were beyond the domain of dynamic high-pressure techniques.

Early in the 1970s, during an interinstitute workshop (then conducted by Academician N N Semenov) in Chernogolovka, which assembled scientists from all institutes of the scientific center, the issue of semiconductor plasmas came under discussion. Partway through the reports, it became clear that very little was known about the physical properties of a dense plasma with a strong interparticle interaction, its phase composition, or its thermodynamics. A heated debate arose, and we suggested carrying out dynamic experiments in this area, noting, among other things, that critical point parameters are known for only three of all metals, which account for 80% of all elements of the Periodic Table.

Academician N N Semenov, who had been calmly leading the discussion and sipping his strong tea, became downright anxious: "It's simply a scandal! This can't be true! You are mistaken. Even before the War, Zeldovich and I talked about measurements of the critical points of metals. Has nothing been done since then? I'm going to give him a call!" Some twenty minutes later Nikolai Nikolaevich returned to the lecture hall in a yet more sad mood to say that Zeldovich confirmed the absence of data on the near-critical parameters of metals; critical point parameters are extremely high and unattainable for the conventional techniques of a physical experiment! Zeldovich told Semenov that this was an interesting and arduous area and that he and Landau [16] had predicted metallization-related phase transitions in the near-critical plasma. At that time, Zeldovich even conceived the corresponding experiment, and "wanted to shoot a rifle at cesium", but nothing good came out of it, because the plasma

Photo 1. *Third All-Union Symposium on Combustion and Explosion, 5–10 July 1971, Leningrad.* In the forefront are Academician Ya B Zeldovich (at the left) and postgraduate student V E Fortov. One of the authors of this review (V E F), had the luck to get acquainted with Ya B and witness precisely this 'renaissance' period of his shock-wave creative work. Amazing are the power and productivity of the intellect, devotion to science, and charisma of this outstanding personality, who determined the appearance, state, and prospects of shock and detonation wave science for many years to come.

I (V E F) got to distantly know Ya B somewhere in the mid-1960s, when we — the students of the Aerophysics Department of the Moscow Institute of Physics and Technology (MIPT) — were taking the classified course in physical gas dynamics, which was intended to prepare specialists in the area of nuclear and plasma rocket engines, as well as the aerodynamics of atmospheric entry of warheads and space vehicles. Well, a good half of the necessary material was contained in the just published monograph by Ya B Zel'dovich and Yu P Raizer [4], which was widely tapped by our lecturers and which I saw on the worktables of rocket technology developers in the then supersecret Research Institute No. 1 (presently the M V Keldysh State Scientific Center).

It was precisely shock-wave research that soon led to our personal acquaintance: developing a nuclear rocket engine with a plasma reactor requires information about the equation of state, transport properties, and composition of the plasma of uranium, hydrogen, and lithium in the domain of high pressures and temperatures. The problem turned out to be arduous and quite basic; our project supervisor, Corresponding Member of the USSR Academy of Sciences V M Ievlev, who was broad-minded and had high physical intuition, set up large-scale research into the basic properties of nonideal plasmas in the Ministry of General Machine-Building Industry.

In one of the then constructed facilities, shock waves were used not only for the compression and heating of cesium plasma, but also for simultaneous measurements of the equation-of-state parameters of the shock-compressed plasma. The data were acquired in a thermodynamically incomplete form, because they did not encompass the temperature and the entropy. The subject of my degree work in MIPT and later on my candidate's thesis was the construction of a thermodynamically complete equation of state from the data of shock-wave measurements, which later came to be known as the 'Fermi–Zeldovich problem'. On accomplishing the task in a rather general form and applying this formalism to the nonideal plasmas of cesium and other metals, I published the results in *Zh. Eksp. Teor. Fiz.* (*J. Experimental and Theoretical Physics, JETP*) [17] and, on completing my postgraduate study, had to radically change the subject of a future research. The absence of a Moscow residence permit and poor prospects for accommodation resulted in my being assigned to the Vladivostok Institute of Automation. I bought a ticket and received the traveling allowance. It only remained for me to deal with a mere formality: to make a twenty minute report at the Symposium on Combustion and Explosion in Leningrad and be through with the shock-wave research area, by all appearances, forever.

The small lecture room was crowded, but sitting alone in the first row was a middle-aged, thickset, lively man, who interrupted the speaker and led the discussion in an uninhabited manner, with elements of aggressiveness and pressure. I also caught it, but not knowing that this was 'Zeldovich himself' I was not perfectly politically correct, either. In short, we had a heated argument, and when it was told to me who my opponent was I lost the gift of speech. After my report and the altercation, Ya B continued the discussion in the corridor in a calm and benevolent manner, suggesting several new substantial problems in elaboration of the report. I refused with apologies and told him about my impending departure and change of research subject. "I'll make all arrangements now!" said Ya B and promptly brought me to the conference lobby to meet Academician N N Semenov and Corresponding Member of the USSR Academy of Sciences F I Dubovitskii, who invited me to continue research work in Chernogolovka. I regard this as my good fortune and throughout my life will feel gratitude to Ya B. I am also grateful for the stroke of luck that brought me into 'Zeldovich's orbit', and I had the fortune of communicating with, working with, and learning from this phenomenal personality for many years.

By the way, in that conversation he drew my attention to his short paper with O M Todes (Ref. [18]), in which he put forward similar ideas and which I had not cited. Ya B blamed me for not knowing that paper, showing the special scrupulousness of the people of this circle (L V Al'tshuler, G M Gandel'man, S B Kormer) to priority issues. This testifies, it seems to me, not only to the natural desire to 'stake out' one's own results, but also more importantly to the great respect for the labor and findings of colleagues and, of course, to one's own labor, as well as to the necessity of the fair appreciation of results, correctness, and standards of human relations in science. This is all somehow vanishing nowadays, both in our country and abroad. People take great interest in self-citing and are prone to overlook the achievements of others. Perhaps these are the side effects of the grant system, which involves a special technique of preparing applications for reviewers and, in the long run, a special method of getting financial support.

Furthermore, Ya B had a phenomenal memory. He was able to name not only the author and volume number of the journal, but also the page where one could learn more about one physical process or another. One day we were discussing my work on the expansion and compression of a material and he said: "You have neglected such-and-such mechanism." "Where can I read about it?" I asked. "In the *Physical Review* journal of 1942." I thought that the journal was unavailable. That was wartime — Stalingrad — the country was busy with other things than scientific journals. I nevertheless went to the library. And what do you know? All 1942 issues were on the shelf! During the War the Government was spending money for scientists to be able to follow the world's scientific achievements and do their work properly.

parameters emerging even in low-boiling cesium were far short of the critical ones. N N Semenov complained about the twists and turns of life and about the slowness of his staff members, gave the 'green light' to our research in dynamic plasma physics, and provided it with his informal support till the end of his days. Someone from the audience remarked that this research area was not listed in the institute's research plan, to which Semenov reasonably replied, "once you were not in the plan, either."

This episode, like many of this kind, communicates the spirit of scientific freedom and democracy, which reigned in our Academy in those days and which is so distinct from the opaqueness of today, when primary importance is assigned to 'conceptions', 'priorities', and 'sounding' in lieu of stimulating work. As for the real scientific business, it is floundering about in a bureaucratic mire and, of course, is declining due to the irresponsibility and muddle of the crowd of pseudoscientific parasitic supervisors.

Being full of ideas and highly enthusiastic about science, Ya B would find and attract capable people and fruitfully work with them, paying little attention to formalities, deference to rank, or subordination. This, it seemed to me, annoyed some bosses, for whom he often could not spare a few minutes (primarily for discussing their personal electoral matters), while his pupils and colleagues spent hours in discussions with Ya B and wrote joint papers. I am unaware of the real reasons for the chilly reception he was given at the CPI, but I am convinced, had Ya B found himself in his native Chemical Physics Institute after his 'exodus' from Arzamas-16, our scientific business would have greatly benefited, especially so in view of the 'renaissance' in studying combustion and explosion phenomena, which set in for him and for us in the 1980s.

The work on the critical point of metals was given a strong impetus after Zeldovich's 'telephone' intervention. The method of unloading adiabats emerged, which enabled attaining the near-critical states for many metals and measuring the parameters of the high-temperature portion of their boiling curves in precisely the domain which Landau and Zeldovich considered to be the most difficult and interesting from the viewpoint of metallization and relief manifestation of nonideality effects [16]. It is a cause for regret that Ya B did not see these findings or recent results on the manifestation of a plasma phase transition [19], plasma ionization under megabar pressure [20], or the viscosity of nonideal electromagnetic and quark–gluon plasmas [21].

Feeling strongly the emptiness after Yakov Borisovich's death, we must be extremely thankful to Ya B Zeldovich for what he gave us all in science and in life: for the example of impeccable conduct in painful and ambiguous situations, and for the opportunity (forever lost!) to simply call him and talk about new results — he would appreciate it! It is precisely Ya B whom we would have wished to tell about some new results discussed in the following sections of this brief review.

2. Shock waves and extreme states of matter

The equation of state, governing the functional dependence among the parameters that characterize the state of a substance, is the main quantitative characteristic of a substance, which makes it possible to apply the general formal body of thermodynamics and dynamics of continuous media (mathematical physics) to describe different physical objects and processes of a highly diverse nature — from heat engines and biological structures to ultraextreme Big Bang conditions and relativistic hadronic collisions [11, 22].

Conservation laws reflect the most fundamental space-time symmetry properties (the Noether theorem). The mass, momentum, and energy conservation laws reflect the totality of processes in the surrounding environment in the most general form, while the equation of state (EOS) introduces into this general formalism the concrete quantitative characteristic of precisely the given (concrete) state of a substance: gas, liquid, solid, electromagnetic or quark–gluon plasma, or nuclear matter radiation. That is why interest in the EOS of matter has always been keen, not only from the standpoint of numerous pragmatic (technical and energy) applications but also from the viewpoint of understanding and describing processes and phenomena under extremely high energy densities: at the stages of the Big Bang, as well as at the final evolution stages of astrophysical objects (neutron stars, black holes), when ultrahigh pressures and temperatures of nuclear substances are realized under gravitational contraction and thermonuclear energy liberation [5, 10, 23–30]. The revolutionary discoveries made in astronomy in recent decades [5, 10, 13, 26–35] (neutron stars, pulsars, black holes, wormholes, γ-ray bursts, exoplanets) revealed new examples of extreme states, whose study is required to solve the basic problems of modern astrophysics.

The commencement of high-pressure research in the 20th century is associated with the pioneering work of P Bridgman [36], who was awarded a Nobel Prize in Physics 1946 * "for the invention of an apparatus to produce extremely high pressures, and for the discoveries he made therewith in the field of high pressure physics." These investigations of compressibility and other physical properties of substances were performed under static pressures on the order of 10 GPa.[1] We cannot help but admire the foresight of the classicist, who wrote [39]: "There is no doubt that the highest pressures will be reached in the future by way of one use or another of shock waves."

And this time did come so soon: even beginning in 1945, measurements of the shock compressibility of substances at pressures of several dozen GPa were undertaken in the Los Alamos National Laboratory, and similar systematic work

* Interestingly, back in 1918, i.e., 28 years prior to the awarding of a Nobel Prize to Percy Bridgman, in the very first volume of the journal *Uspekhi Fizicheskikh Nauk* (*UFN*), *UFN*'s founder and editor (Academician P P Lazarev) and his assistants (the curators — an analogue of the *UFN*'s present-day editorial board — Academicians A N Krylov and P I Val'den) considered it necessary to tell the readers of the journal about Bridgman's work (as of one of the most outstanding successes in the experimental physics of those days!) and publish in the first three successive 1918 issues a comprehensive review, "Bridgman's research in the area of high pressures" by A V Rakovskii [37]. Its concluding words read: "Judging by Bridgman's papers, in the near future one would expect from him not only new experimental research, but also several theoretical studies in the field under his investigation. It only remains for us to patiently wait and to wish further success to the young (born in 1882) American scientist" [37, p. 203]. And in 1995, conversely, an American scientist, R N Keeler, speaks about gifted researchers from Chernogolovka — pupils of Ya B Zeldovich's scientific school — and observes the uniqueness of their work (and a certain similarity to Bridgman's work) in the development of an entirely new realm of physics — dynamic physics of dense plasmas [38, p. 597]. (*Editor's note*.)

[1] Along with pressure units of the SI, in high-pressure physics use is also made of off-system units, in particular, of bars and atmospheres, with 1 bar $= 10^5$ Pa $= 0.987$ atm.

was independently commenced in the Russian Federal Nuclear Center (Arzamas-16) in 1948. Ya B was one of the pioneers — the founders of the shock-wave area of research. The highest pressures reached in shock-wave experiments to date are a thousand times higher than the static limits.

When use is made of dynamic — shock-wave — techniques, researchers have to deal with situations in which a substance experiences a dynamic action over a short time interval, which is attended with major changes — gradients — in all physical parameters, motion of the medium emerges, etc. In the general form, these processes are described by partial differential equations of gas dynamics, which express the mass, momentum, and energy conservation laws:

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \rho \mathbf{u} = 0\,, \qquad \frac{\partial \rho \mathbf{u}}{\partial t} + \operatorname{div}(\rho \mathbf{u} \times \mathbf{u} + \pi) = 0\,,$$
$$\frac{\partial \rho (E + u^2/2)}{\partial t} + \operatorname{div}\left[\rho \mathbf{u}\left(E + \frac{u^2}{2}\right) + \pi \mathbf{u}\right] = 0\,, \tag{1}$$

where $\partial/\partial t$ is the designation of the local, i.e., relating to a given point in space, partial time derivative, ρ is the substance density, $\mathbf{u} = (u_x, u_y, u_z)$ is the velocity vector, and $\pi = (\pi_{ik})$ is the stress tensor.[2] System (1), which is closed by the equation of state, $E = E(p, \rho)$, is solved, as a rule, numerically.

In the case of a self-similar flow, equations (1) are simplified, and so experimentalists seek to realize precisely the self-similar regimes in dynamic experiments. Of practical significance is the case of a stationary shock wave [4].

A shock wave is a special physical object with unique properties. When a stationary shock discontinuity propagates through a substance, the mass, momentum, and energy conservation laws are fulfilled at its front [4]. These laws relate kinematic parameters — the velocity D of the shock wave and the mass velocity u of the substance behind its front — with thermodynamic quantities — the specific internal energy E, the pressure p, and the specific volume V — by simple algebraic expressions:

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

where the subscript 0 applies to parameters of the immobile substance ahead of the shock front. Equations (2), which have come to be known as the Hugoniot laws, permit determining the hydro- and thermodynamic characteristics of the substance by measuring any two of the five parameters E, p, V, D, and u. The shock wave velocity D is measured most easily and accurately applying basic techniques. The choice of the second parameter to be measured depends on specific experimental conditions; the result of measurements and application of relationships (2) is the caloric EOS: $E = E(p, V)$.

Another important self-similar solution applies to the case of a centered Riemann rarefaction wave [4]. In experiments to determine the curves of isentropic expansion of a shock-compressed substance [23, 26], the states in the centered unloading wave are described by the Riemann integrals [4]

$$V = V_{\mathrm{H}} + \int_p^{p_{\mathrm{H}}} \left(\frac{\mathrm{d}u}{\mathrm{d}p}\right)^2 \mathrm{d}p\,, \qquad E = E_{\mathrm{H}} - \int_p^{p_{\mathrm{H}}} p\left(\frac{\mathrm{d}u}{\mathrm{d}p}\right)^2 \mathrm{d}p\,, \tag{3}$$

which are calculated along the measured isentrope $p_s = p_s(u)$ (V_{H}, p_{H}, and E_{H} are, respectively, the specific volume, pressure, and internal energy of the initial state in the shock Hugoniot). By performing measurements for different initial conditions and shock intensities, it is also possible to determine the caloric EOS: $E = E(p, V)$.

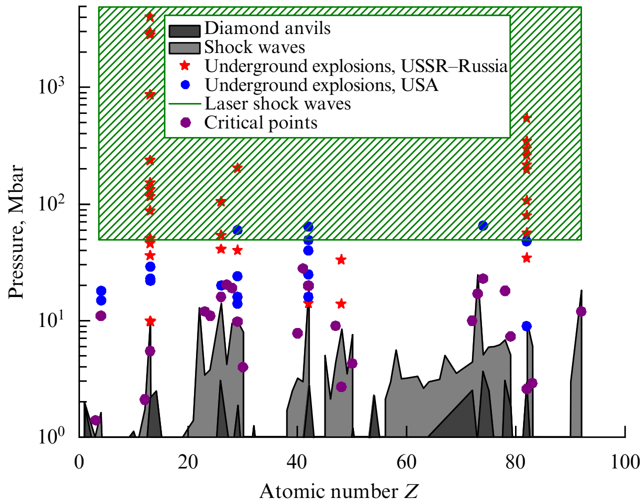

Figure 1. Pressure range investigated for elements. Static pressures — diamond anvils, and dynamic ones — shock waves, underground explosions, laser shock waves.

The methods for measuring the shock compressibility of substances, the problems of generating high and ultrahigh pressures, and the absorbing historical background are comprehensively discussed in monographs [4, 23, 26] and reviews [6, 8–10, 40–49]. These sources consider at length the main development stages of the physics of high dynamic pressures — from the first work of the 1950s, in which pressures of up to 500 GPa were realized using explosive generators, to more recent work on the production and study of extreme states of substances at pressures of several hundred TPa obtained using high-power lasers and underground explosions. The presently attainable pressure range is depicted in Fig. 1. Embodied in these studies is the philosophic tenet of one of the founders of the physics of extreme states of substances, Yu B Khariton, Ya B's colleague and friend: "We must know ten times more than we need to for the solution of practical problems." In Section 3, we shall take a close look at Ya B's fundamental ideas, whose implementation made it possible to fill in the blanks in the physical picture of the phase states of substances.

3. Fermi–Zeldovich problem. Construction of a thermodynamically complete equation of state from the data of dynamic measurements

A typical surface of the $p(V, T)$ thermodynamic potential for aluminum is plotted in Fig. 2. Only the line of a principal shock Hugoniot H_1 at megabar pressures was known on this surface by the 1950s. Trustworthy experimental or theoretical information on the properties of crystal, liquid, or plasma at

[2] We note that the stress tensor is spherical in the hydrodynamic approximation: $\pi_{ik} = p\delta_{ik}$, where δ_{ik} is the Kronecker symbol.

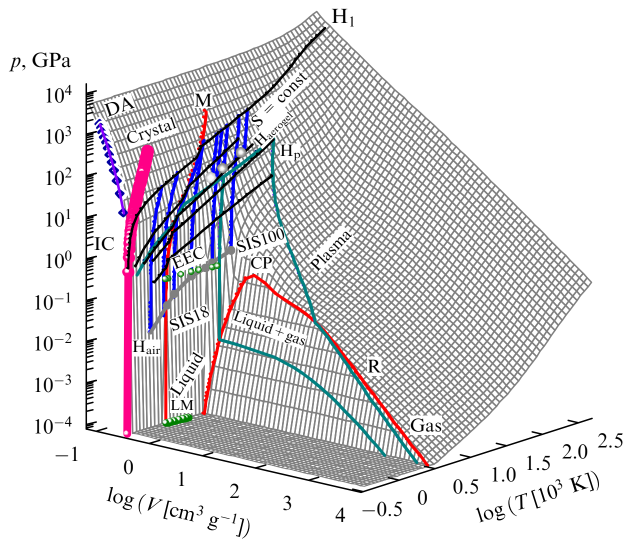

Figure 2. Aggregate states of a substance: M — melt domain; R — boundary of the two-phase liquid–vapor domain with a critical point (CP); H_1 and H_p are the shock Hugoniots of crystalline and porous aluminum; H_{air} and $H_{aerogel}$ are the air and aerogel shock Hugoniots; DA — measurements of isothermal compressibility in diamond anvils; LM — liquid metal density measurements at room pressure; IC — isentropic compression; EEC — electric explosion of conductors — experiments on the isobaric expansion of aluminum wires heated by a high-current pulse; S — unloading isentropes; SIS18 and SIS100 — domains attainable in heavy ion beam experiments at SIS18 and SIS100 accelerators.

high pressures and temperatures, as well as on the positions of phase boundaries of melting, evaporation, and the critical point, was completely lacking. Strictly speaking, the position of H_1 was also rather arbitrary.

A characteristic feature of dynamic experiments, which are the basis for the construction of semiempirical EOS models, lies in the fact that experimental data permit obtaining the equation of state of a substance only in a thermodynamically incomplete form: $E = E(p, V)$. This is because the internal energy E is not a complete thermodynamic potential relative to variables p and V, and so to elaborate closed thermodynamics requires additional information about the temperature $T = T(p, V)$ [4] or entropy $S = S(p, V)$, which is vital for the development of adequate semiempirical equations of state.

The point is that dynamic methods of investigation [4] rely on the measurement of mechanical parameters of hydrodynamic motion, which do not yield information on the thermal or entropic characteristics of a shock-compressed substance.

Dynamic diagnostic techniques, which are based on general conservation laws, permit reducing the problem of determining the caloric EOS: $E = E(p, V)$ to the measurement of kinematic parameters of the motion of shock waves and contact surfaces, i.e., to the measurement of distances and times, which may be done with a high accuracy. As noted above, the internal energy, however, is not a thermodynamic potential relative to p and V variables, and so to work out the closed thermodynamics of a system renders determination of additional dependence $T(p, V)$ of the temperature.

In optically transparent and isotropic media (gases, ionic crystals, etc.), the temperature is measured simultaneously with other shock compression parameters. Condensed media, first and foremost metals, are opaque, as a rule, so that the optical radiation of these shock-compressed media does not lend itself to measurements.

In accordance with Fermi's [50] and Zeldovich's [3] suggestions, the thermodynamically complete equation of state may be constructed directly from the data of dynamic measurements, without invoking *a priori* considerations about the properties and character of the substance under investigation [23, 26], proceeding from the first law of thermodynamics and the $E = E(p, V)$ dependence known from the experiment [or a more convenient function $\gamma(p, V) = pV/E(p, V)$]. This leads to a linear inhomogeneous differential equation for $T(p, V)$:

$$\left[p + \left(\frac{\partial E}{\partial V}\right)_p\right]\frac{\partial T}{\partial p} - \left(\frac{\partial E}{\partial p}\right)_V \frac{\partial T}{\partial V} = T\,, \tag{4}$$

whose solution is constructed by the method of characteristics:

$$\frac{\partial p}{\partial V} = \frac{p + (\partial E/\partial V)_p}{(\partial E/\partial p)_V}\,, \qquad \frac{\partial T}{\partial V} = -\frac{T}{(\partial E/\partial p)_V}\,, \tag{5}$$

or

$$\begin{aligned} E &= E_0 \exp\left(-\int_{V_0}^{V} \gamma(V, E)\,\mathrm{d}\ln V\right), \\ T &= T_0\,\frac{pV}{p_0 V_0}\exp\left[-\int_{V_0}^{V}\left(\frac{\partial \ln \gamma(E, V)}{\partial \ln V}\right)\mathrm{d}\ln V\right]. \end{aligned} \tag{6}$$

Equations (4)–(6) are supplemented with initial conditions: the temperature is prescribed in the low-density domain, where it may be safely calculated (cesium plasma), or it is known from a static experiment [23, 26].

The $E(p, V)$ dependences required for calculating the right-hand sides of Eqns (5) and (6) were determined from experimental data in the form of power polynomials

$$\sum_i \sum_j a_{ij}\, p^i V^j\,,$$

and in the form of linear fractional functions for $\gamma(E, V)$.

The accuracy of the resultant solution in relation to experimental errors and uncertainties of initial data was determined by numerical Monte Carlo simulations of the probabilistic structure of measurements [23, 26].

This thermodynamic method is general in character — it is free from restrictive assumptions about the properties, character, and phase composition of the medium under investigation, because it is based on the first principles of the mechanics of continua: the conservation laws (2), (3) and the fundamental thermodynamic identity (4). This thermodynamic universality has made it possible to derive the equations of state for a variety of condensed media with the use of a single method and to apply it to the description of phase transitions [23, 26]. This method proved to be particularly efficient for studying the thermodynamics of nonideal cesium plasma [23] on the basis of experiments on the shock and adiabatic compression of the saturated vapors of the base and transition metals, ionic crystals, and silicon oxide. The results of this kind of calculations for tungsten are given in Fig. 3.

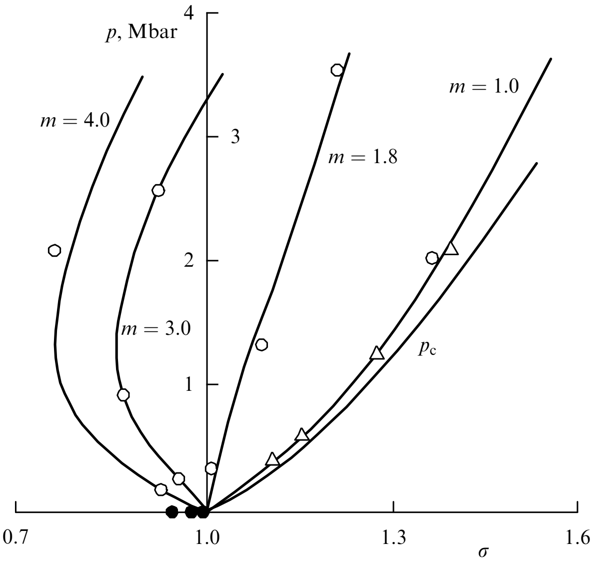

Figure 3. Phase diagram of tungsten, according to Ref. [51], in the pressure (p)–compression ratio (σ) plane, where $\sigma = V_0/V$, and V_0 is the specific volume under normal conditions. The curves stand for the shock Hugoniots of a porous metal at different values of a degree of porosity m indicated alongside of the curves ($m = V_{00}/V_0$, and V_{00} is the initial specific volume of the porous substance). p_c depicts the cold compression curve. Different symbols represent experimental data.

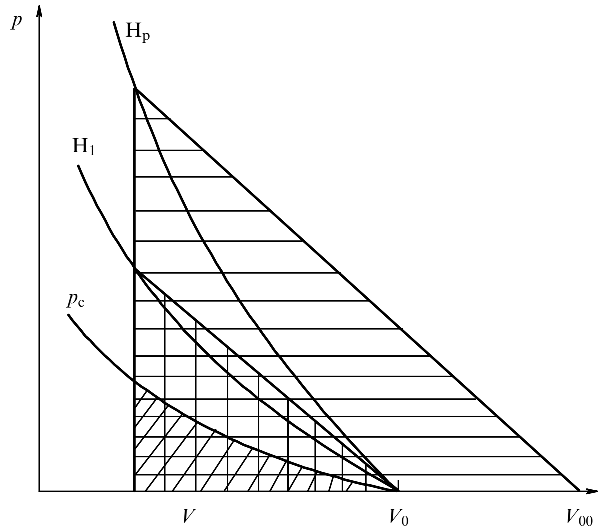

Figure 4. Pressure–specific volume diagram of the shock compression of a porous substance according to Ref. [4]. H_p and H_1 are the shock Hugoniots of porous and crystalline substances, and p_c displays the cold compression curve. The horizontal hatching shows the internal energy acquired in the shock compression of the porous substance, the vertical one demonstrates that acquired in the shock compression of the crystal, and the oblique hatching exemplifies the elastic energy.

4. Shock compression of porous substances

In the 1950s, Ya B came up with the idea of experimentally investigating the shock compression of the same substance at different initial densities [4]. In this case of shock compression of the porous substance, there is a fan of shock Hugoniots H_p, which cover a different domain of the phase diagram and have a lower density relative to the principal shock Hugoniot H_1 (see Fig. 2). The idea of the method is presented in Fig. 4. It is physically clear from the geometrical consideration of the shock compression of a porous sample that an increase in substance porosity under the compression to the same finite volume V enhances the thermal part of the energy and, accordingly, the thermal component of the pressure.

Ya B also analyzed the influence of thermal effects on the position of a shock Hugoniot in the phase plane and theoretically predicted the effect of anomalous shock compression of a porous substance, proceeding from simple physical considerations about the EOS form. It turned out that the shock compression of a low-density substance results in a so high thermal pressure that the density in the final state becomes lower than the normal one. This anomalous run of the shock Hugoniot was experimentally borne out even in the first investigations of the shock compressibility of porous metals: tungsten [52], aluminum, copper, nickel, and lead [53].

The systematic study of the shock Hugoniots of porous substances performed later on (see, for instance, Refs [44, 54–68]) permitted obtaining reference information for constructing wide-range EOSs and considerably extended our knowledge about the thermodynamic properties of dense liquids and plasmas. For instance, simultaneously with the acquisition of data about the properties of liquid metals at the megabar pressures of shock compression [53], a semiempirical EOS was constructed for metals with the inclusion of the variable heat capacity of lattice atoms and the contribution of conduction electrons.

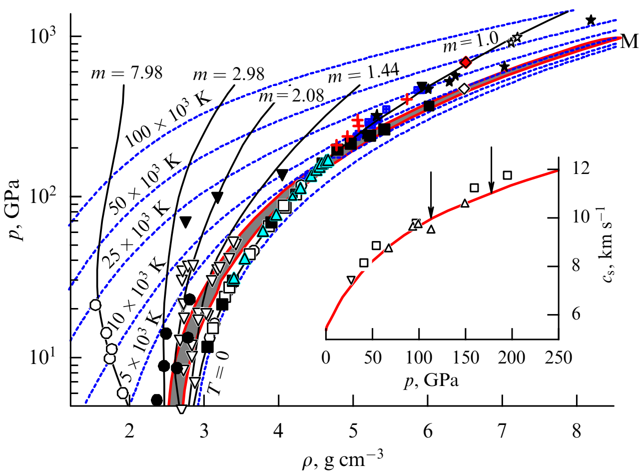

Figure 5. Phase diagram of aluminum at high pressures. Data calculated from the EOS: isotherms (dashed curves) at temperatures indicated in the drawing and the shock Hugoniots of porous samples (solid curves) for degrees of porosity m indicated alongside the curves; M is the melting domain. Symbols stand for experimental data. The inset shows the velocity of sound $c_s(p)$ in shock-compressed aluminum: calculation by the EOS (curve), and experimental points (symbols); arrows indicate the melting location in the shock wave.

It is noteworthy that taking account of the anharmonicity effects of thermal atomic vibrations was evaluated from the thermal-to-elastic energy constituent ratio and was performed on the basis of shock compression data for porous substances. Figure 5 serves to illustrate the quality of calculating the phase diagram of aluminum at high pressures with the employment of a multiphase EOS [69].

It is instructive to compare in the phase diagram the compressibility measurement data of a porous substance and a liquid metal heated to a high temperature. These experiments were carried out on low-melting metals: zinc, tin, lead,

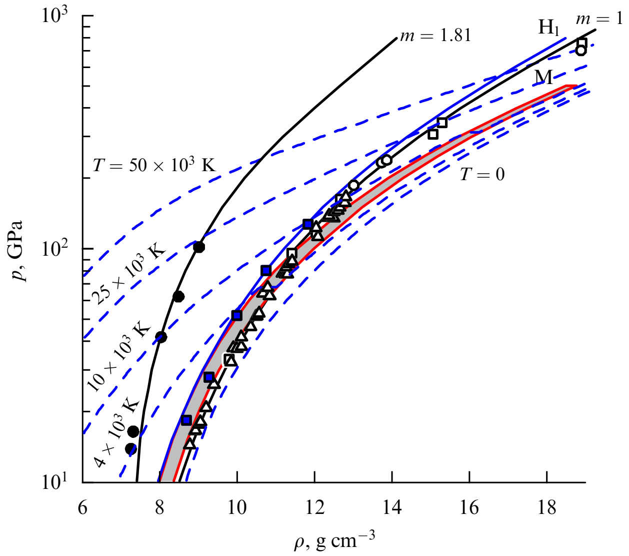

Figure 6. Phase diagram of tin at high pressures. Calculation by the EOS: isotherms (dashed curves) at temperatures indicated in the drawing; shock Hugoniots of porous samples (solid curves) for degrees of porosity $m = 1$ and 1.81; H_l is the shock Hugoniot of liquid metal; M is the melting domain. Symbols stand for experimental data.

cadmium, and bismuth [70, 71]. As evident from Fig. 6, a considerable increase in initial temperature permits investigating the phase diagram domain which corresponds to a compressed liquid substance near the melting domain. However, a comparison of the shock Hugoniots of liquid and porous metals clearly illustrates the advantages of Ya B's idea: the compression of a porous substance leads to substantially stronger thermal effects in pressure and energy, making it possible to shift farther from the principal shock Hugoniot and cover a greater density range in the phase diagram.

Unique results were obtained in the investigation of the shock compressibility of strongly porous nickel: the shock Hugoniots of samples with initial densities 10 to 28 times lower than the normal one were investigated at megabar pressures in Refs [62, 63, 68]. The final states of shock-compressed nickel fall in the density range up to 0.2 of the normal density and in the pressure range down to 90 GPa, which corresponds to high temperatures of up to 10^5 K. Realized under these conditions are the states of not only a dense hot fluid but also, according to calculations by a chemical plasma model [63], of ionized metal with a degree of ionization $\alpha \leqslant 1$ and a Coulomb nonideality parameter $\Gamma = E_C/E_k \approx 0.1-1.0$, where E_C is the energy of Coulomb interparticle interaction, and E_k is the kinetic energy (Fig. 7).

An utterly special place in the phase diagram is occupied by the unique data of measuring the shock compressibility for porous copper, iron, and tungsten with a porosity $m = 3-4$, which were obtained in conditions of underground nuclear explosions [42, 56, 61]. In these experiments, the final density in the shock Hugoniot is close to the normal one at extremely high pressures (in the terapascal range) and a temperature of $\lesssim 3 \times 10^5$ K (Fig. 8). According to estimates reported in Refs [42, 56, 61], the states with a dominant contribution of the electron component, corresponding to a weakly degenerate electron gas with an extremely high specific energy density of ~ 1 MJ g^{-1}, were realized in the experiments.

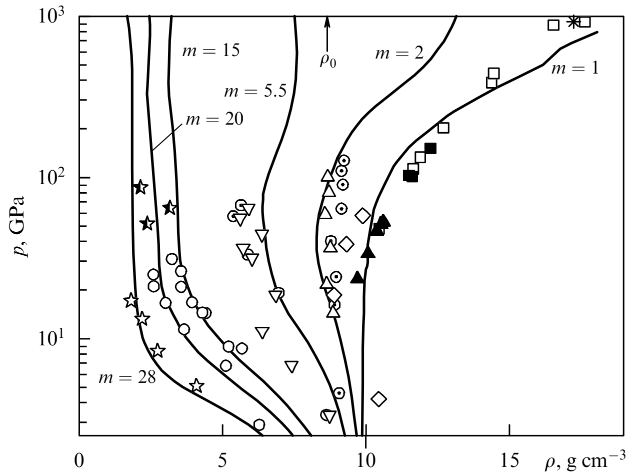

Figure 7. Shock Hugoniots (solid curves) of porous nickel calculated in the framework of the chemical plasma model [63]; $m = V_{00}/V_0$. Symbols stand for experimental data.

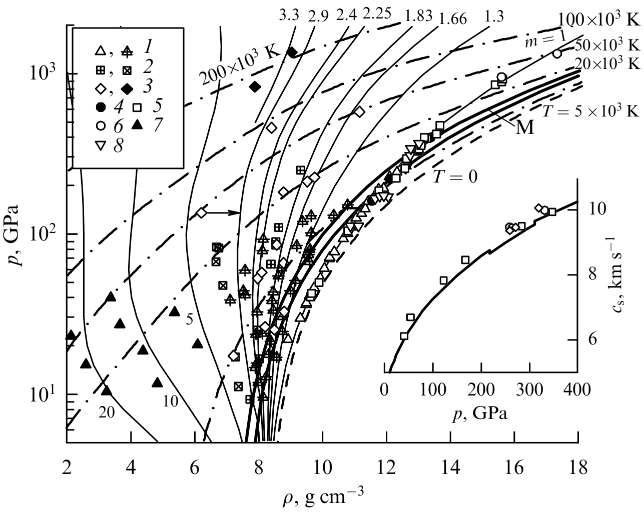

Figure 8. Phase diagram of iron at high pressures. Calculation by the EOS: isotherms (dash-dot curves) and shock Hugoniots (solid curves) of porous samples for different values of the degree of porosity m indicated in the drawing; M is the melting domain. Symbols stand for experimental data: *1–2*, *5–8* — shock compression with the help of chemical explosives, *3* — the data of Ref. [61] (white diamonds — shock compression using chemical explosives, black diamonds — data obtained in underground explosions). The inset shows the velocity of sound $c_s(p)$ in shock-compressed iron: calculation by the EOS (curve), and experimental points (symbols).

Therefore, the embodiment of Ya B Zeldovich's idea [4] made it possible not only to place reference points into the phase diagram for lower substance densities than those in the shock Hugoniot of a crystal, but also to investigate diverse physical states like dense fluids, nonideal plasmas, and weakly degenerate electron gases.

5. Isentropic expansion of shock-compressed substances

Away back in 1945–1948, American and domestic researchers managed to experimentally realize the self-similar flow in the form of a stationary shock wave described by Hugoniot laws (2) and begin extensive measurements of the shock Hugoniots

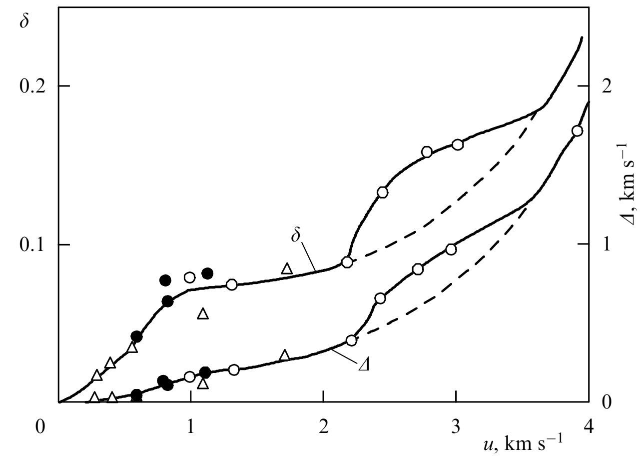

Figure 9. Vaporization of lead upon unloading into the air [72]. $\Delta = w - 2u$, $\delta = \Delta/2u$, where w and u are the final and initial wave expansion velocities (of unloading into the air, and the mass velocity in the shock Hugoniot). Solid curves correspond to the equilibrium state, and dashed curves to the metastable one. Symbols stand for experimental data points.

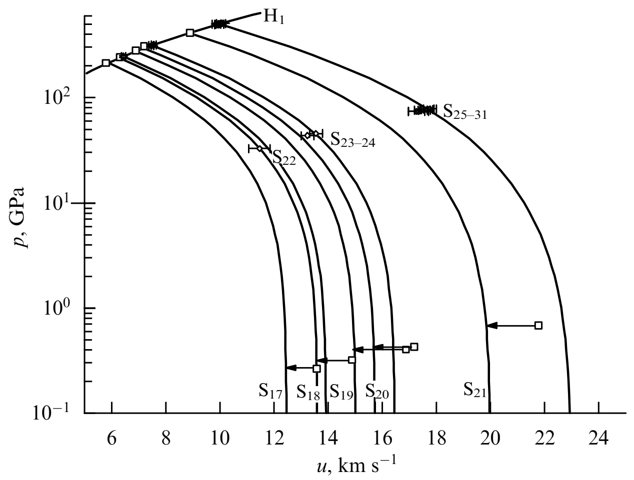

Figure 11. Unloading isentropes of liquid aluminum. Curves demonstrate calculations by the EOS, H_1 is the principal shock Hugoniot, and S_i are unloading isentropes. Experimental data: squares — [59], and diamonds — unloading into an aerogel [76]. Arrow indicates the isentrope to which an experimental point refers.

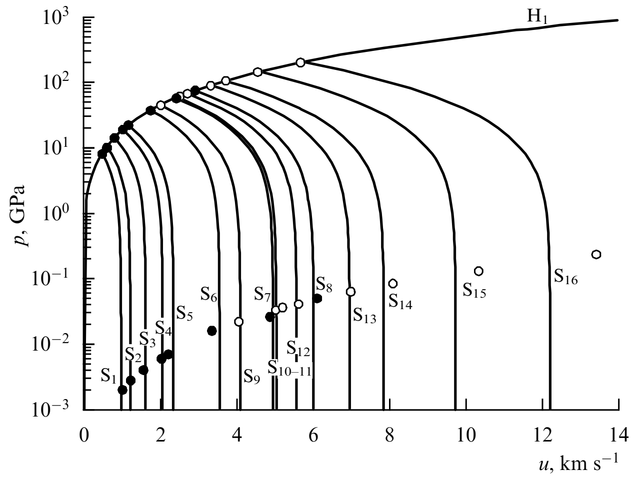

Figure 10. Unloading isentropes of solid and melted aluminum. Curves fit the data of calculations by the EOS, H_1 is the principal shock Hugoniot, and S_i are unloading isentropes. Black dots stand for the experimental data of Ref. [74], and white dots for those of Ref. [73].

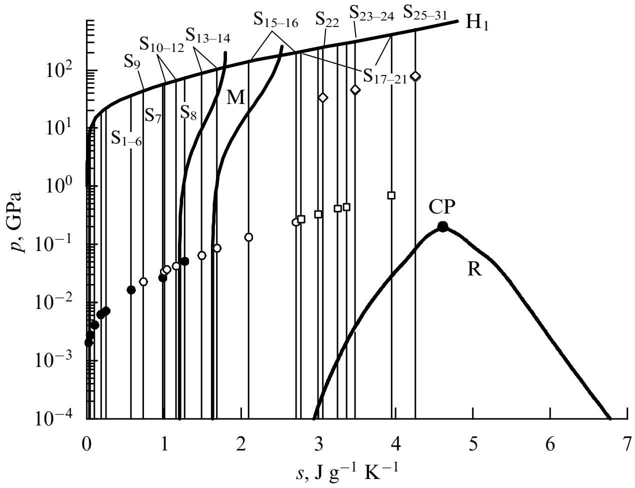

Figure 12. Pressure (p)–entropy (s) diagram of aluminum. Curves fit the data of calculations by the EOS, H_1 is the principal shock Hugoniot, and S_i are unloading isentropes; M is the melting domain, R is the two-phase liquid–vapor domain with the critical point (CP). Symbols correspond to the experimental data points shown in Figs 10 and 11.

of substances. In the realm of the second invariant of gas dynamic equations (4)–(6) — relations (3) for the centered Riemann rarefaction wave — Ya B Zeldovich's idea [3] was implemented much more recently. Today, it is possible to put emphasis on two experimental techniques for investigating the EOS of a substance under isentropic expansion.

In the first case, the initial and final points in the isentropes, i.e., in the shock Hugoniot and in the expansion into an obstacle of fixed stiffness, are determined in a wide range of shock compression pressures. In particular, investigating the expansion into the air, it was possible to determine the expansion isentropes of lead, aluminum, copper, iron, molybdenum, tantalum, and carbon from different pressures of shock compression [59, 72–75]. For lead (Fig. 9), a conclusion was drawn about vaporization in the unloading wave at a pressure above 1.32 Mbar due to the presence of characteristic nonmonotonities in the dependence of the velocity of expansion into air on the mass velocity in the shock-compressed substance [72]. For metals with higher melting and vaporization parameters than for lead, no variation in the slope of unloading isentropes (and hence no vaporization effect) is observed.

By way of example, we give the results of calculations by the wide-range EOS [69] for the isentropic expansion of aluminum from solid (isentropes $S_1 - S_{14}$ in Fig. 10) and liquid (isentropes $S_{15} - S_{31}$ in Fig. 11) phases for different initial pressures of shock compression. Indeed, the final states in isentropic unloading waves (S_{1-31}) are located in the entropy diagram (Fig. 12) above the vaporization domain, and aluminum does not vaporize in the unloading into the air, which is also clear from Fig. 2.

Domestic researchers developed different types of standard explosive generators of shock waves [9, 43–46]. With their aid, the method of isentropic expansion (3) is implemented in full measure in accordance with Ya B's idea [3]: for a concrete isentrope, the expansion velocities are measured at

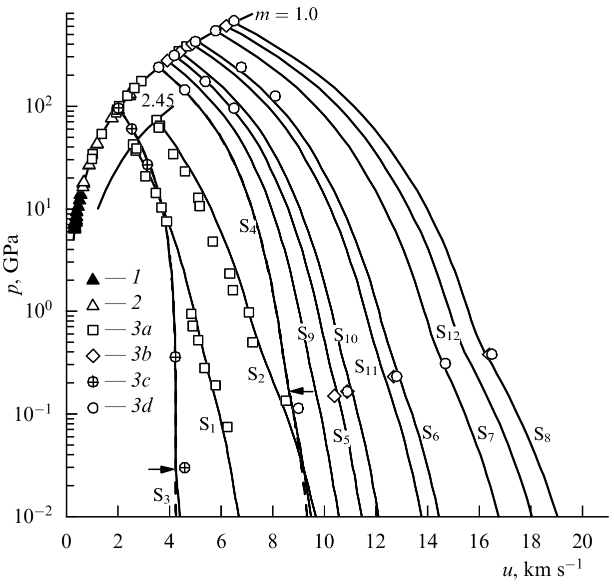

Figure 13. Shock Hugoniots ($m = 1$ and 2.45) and unloading isentropes S_i (solid curves — equilibrium, dashed curves — metastable) of bismuth. Arrows indicate entry into the two-phase liquid–vapor domain. Different symbols represent experimental data: points *1* and *2* were obtained in the shock compression, points *3a* and *3c* using plane shock-wave generators, *3b* and *3d* using multistage and conic ones, respectively.

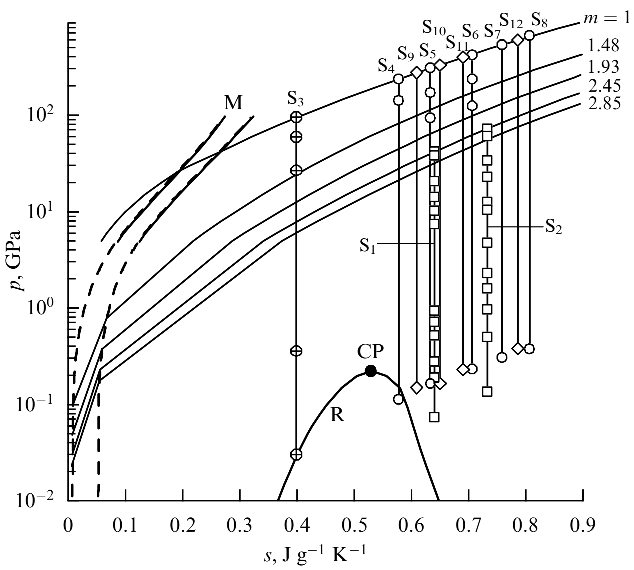

Figure 14. Pressure (p)–entropy (s) diagram of bismuth. Results of calculations by the EOS: unloading isentropes S_i and shock Hugoniots for different values of porosity $m = V_{00}/V_0$ indicated alongside the curves; M is the melting domain, and R is the two-phase domain with the critical point (CP). Symbols correspond to the experimental data points shown in Fig. 13.

different unloading pressures $p_s = p_s(u)$. To this end, the substance states emerging in the isentropic expansion of the sample under investigation from one point in the shock Hugoniot into obstacles with different stiffnesses are measured in a series of experiments. Already in the first experiments performed in this arrangement [57], high-energy states of copper and lead were realized in a broad parameter interval in the vicinity of the liquid–vapor equilibrium line, with the requisite high entropy value at the initial point in the shock Hugoniot and, accordingly, in the isentrope obtained through the use of porous samples. For obstacle media, use was made of condensed materials like plexiglass, polyethylene, foamed plastics, as well as air and rare gases, with known EOSs at different initial pressures.

The resultant data covered the previously unexplored domain of the phase diagram: four orders of magnitude in pressure, three in density, and four in temperature — from the domain of a hot dense liquid characterized by ion disordering and electron degeneracy to the domains of a nonideal plasma, vaporization with the critical point, quasiideal Boltzmann plasma, and low-density metal vapor.

As the system expands, electron degeneracy is removed, the energy spectrum of atoms and ions is appreciably rearranged, and a partial recombination of the dense plasma occurs. In the disordered electron system, a metal–dielectric transition manifests itself, and a plasma nonideal relative to different kinds of interparticle interaction in the neighborhood of the liquid–vapor equilibrium line and critical point forms. The entry of isentropes into the two-phase liquid–vapor domain is attended with vaporization, and the entry from the side of the gas phase is attended with condensation, resulting in a change in the slope of experimental pressure dependences of the unloading wave velocity.

The phase diagram domain under investigation was broadened in the subsequent experiments on aluminum, bismuth, and copper [59, 77]. Figure 13 shows the data on the isentropic expansion of bismuth, and Fig. 14 demonstrates the positions of shock Hugoniots and isentropes in the entropy diagram. Calculations made in the framework of a 'chemical' plasma model [23, 26, 78–80] suggest that the final states in isentropes S_2, S_7, S_8, and S_{12} correspond to weakly nonideal low-density plasmas with the degree of ionization $\alpha \approx 10^{-2}-10^{-1}$. The equilibrium properties of such bismuth plasma are calculated with a rather high degree of reliability using conventional methods of statistical physics, making it possible to describe, proceeding from the data of mechanical measurements [59], the thermodynamic properties of substances, and thereby to solve the Fermi–Zeldovich problem.

An alternative possibility to close the thermodynamic description appears, as evident from Eqn (6), if the temperature is measured in the isentropic unloading wave. It is pertinent to note that the temperature measurements are valuable on their own.

Figure 15 serves to compare the calculated and experimental unloading isentropes of lead [81] in the domain of vaporization and the vicinity of the critical point. As is clear from the drawing, temperature measurements in isentropic unloading waves permit experimentally determining the position of the vaporization domain throughout the temperature range up to the critical one. This fact is borne out by the good consistency of measurement data obtained at different initial pressures of shock compression and, accordingly, at different positions of isentrope entry into the two-phase liquid–vapor domain from both the liquid side and the plasma side.

The subsequent experimental research leaning upon the method of isentropic expansion of shock-compressed substances permitted obtaining reference data for constructing the EOS for metals [67, 74, 82–85] and organic compounds [86–88].

Ya B's idea also underlies the method for isochoric heating by intense heavy-ion beams, followed by isentropic

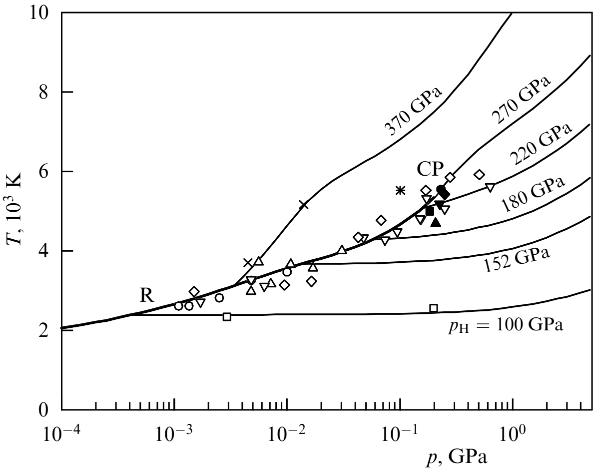

Figure 15. Pressure–temperature phase diagram of lead. The curves fit the data of calculations by the EOS; R is the liquid–vapor domain with the critical point (CP), p_H is the pressure in the shock Hugoniot (the corresponding values are indicated alongside the curves). White symbols stand for experimental points [81], and black symbols for estimates of the critical point.

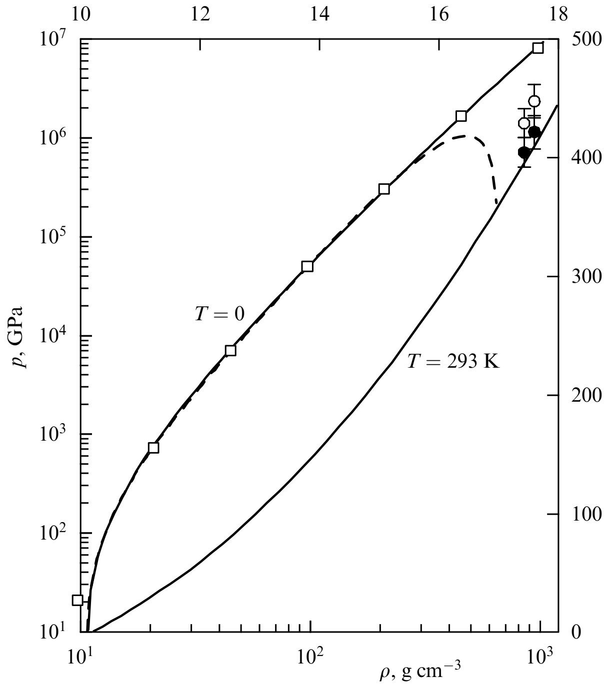

Figure 16. Pressure in molybdenum at $T = 0$ (the left and lower coordinate axes) and $T = 293$ K (the right and upper coordinate axes). Solid curves — calculation by the EOS; dashed curve — result borrowed from Ref. [101]; squares — calculation by the Thomas–Fermi theory [100]; circles with error bars — data on compression in diamond anvils without corrections (black circles) and with corrections (white circles) for nonhydrostaticity.

expansion (HIHEX — Heavy Ion Heating and Expansion) [89, 90].

6. Model equations of state of substances

The modern state of the problem of theoretical computation of EOSs of substances in a broad domain of the phase diagram is reflected in monograph [91]. It is noteworthy that recent years have seen remarkable progress in the calculations of phase diagram domains using sophisticated methods of density functional and quantum molecular dynamics. However, the problem of end-to-end coverage (in the framework of one theoretical method) of the entire phase plane, from the compressed crystal domain to the domains of a hot fluid, nonideal plasma, and quasiideal gas states, still remains to be solved. That is why a wide utility in practice have found semiempirical EOS models [69, 91–98] in which the thermodynamic potential is represented in an analytical form or is calculated in a self-consistent manner in the entire phase plane. In these models, the functional dependences rely on the results of rigorous theories and ensure physically correct asymptotic behavior in different limiting cases. Numerical coefficients are in part the values of individual substance characteristics, and in part the parameters adjusted to best fit the data of rigorous theoretical calculations to the totality of the experimental data. Methodic requirements, construction principles, and examples of EOS calculations are expounded at length in monographs [91, 96, 98] and reviews [69, 97, 99]. We shall illustrate the approach proposed by the example of the multiphase EOS of molybdenum.

The EOS model defined in the form of free energy thermodynamic potential [69, 95, 97] takes into account the contributions of the elastic component at $T = 0$, lattice atoms and conduction electrons, and the most important physical effects: the anharmonicity of thermal vibrations of lattice atoms, melting, vaporization, and ionization. The majority of EOS coefficients, which are characteristic constants of every metal (atomic weight, nuclear charge, the density at normal conditions, etc.) are borrowed from reference books; the remaining ones are found by best fitting the most significant experimental data and reproducing the theoretical asymptotic behavior. The following high-temperature and high-density information is invoked to develop the equation of state: measured isothermal compressibility in diamond anvils, data on the density and the velocity of sound in liquid metals, results of $p - T$ phase diagram measurements under static conditions, isobaric expansion data, data on the shock compressibility of continuous and porous samples in incident and reflected waves, comparative data on the shock compressibility obtained from underground nuclear explosions, data on the isentropic expansion of shock-compressed metals, and estimated critical point parameters. Furthermore, use is made of calculated results found by the Thomas–Fermi theory, different band theories, and the method of quantum molecular dynamics.

Guided by the measurement data on the static and dynamic compressibilities of molybdenum, one may draw a conclusion that the pressure curve appears as smooth and monotonic. This is the reason why the EOS of molybdenum corresponds to the initial parameters of the body-centered cubic phase under room conditions. As is clear from Fig. 16, the elastic compression curve of molybdenum agrees nicely with the results of calculations by the Thomas–Fermi model [100] for compressions up to the 100-fold one, and with an earlier semiempirical dependence [101] for moderate compression ratios. The data for isothermal molybdenum compressibility measurements in diamond anvils are also consistent with theoretical results to within the errors of experiment and data processing. The calculated value of the initial slope of the melting curve, $dT/dp = 3.33$ K kbar^{-1}, is in agreement with the data of experiments on the isobaric

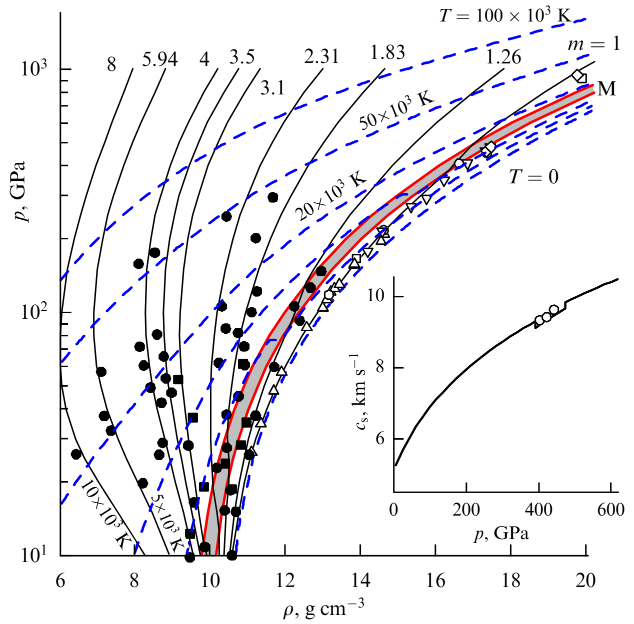

Figure 17. Phase diagram of molybdenum at high pressures. Calculation by the EOS: dashed curves — isotherms at different temperatures; solid curves — shock Hugoniots of porous samples for different porosity values indicated alongside the curves; M is the melting domain. Symbols stand for experimental data. The inset shows the velocity of sound $c_s(p)$ in shock-compressed aluminum: calculation by the EOS (curve), and experimental points (symbols).

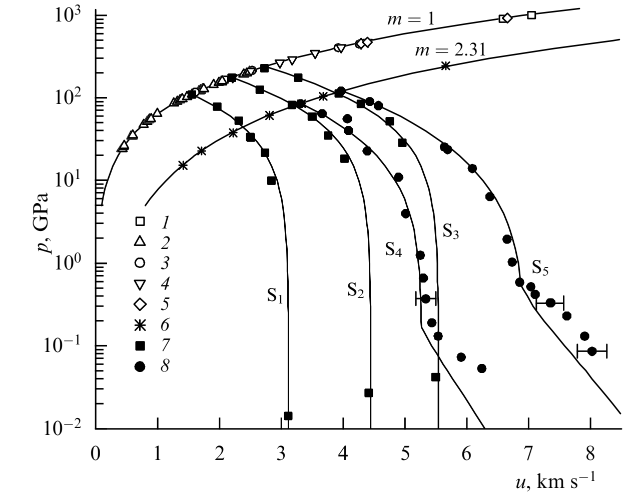

Figure 18. Shock Hugoniots for $m = 1$ and $m = 2.31$ and unloading isentropes (S_i) of molybdenum. Symbols *1–6* correspond to shock compression, *7* to the data of Ref. [74], and *8* to isentropic expansion [106].

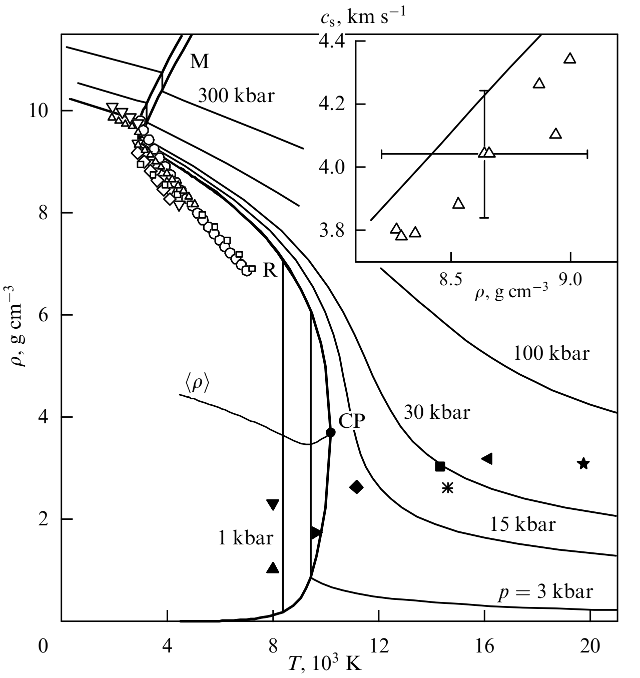

Figure 19. Phase diagram of molybdenum in the lowered-density domain. Thin solid curves — isobars. M — melting, R — vaporization with the critical point (CP). White symbols — experimental data on the electric explosion of conductors; black symbols — estimates of the critical point. The inset shows the velocity of sound in liquid molybdenum at $p = 2$ kbar, and triangles stand for experimental data.

expansion of conductors, $\mathrm{d}T/\mathrm{d}p = 3.4 \pm 0.6$ K kbar^{-1} [102], and the optimization data processing for solid and liquid molybdenum, $\mathrm{d}T/\mathrm{d}p = 3.5 \pm 0.2$ K kbar^{-1} [103].

Domain of densities which are lower than the density in the case of the shock Hugoniot of a crystalline substance was studied in experiments on the shock compression of porous molybdenum samples, as well as of a liquid metal heated to 1673 K. In experiments on measuring the velocity of sound in shock-compressed molybdenum [104], the transverse component was found to disappear at $p = 3.9$ Mbar, which is attributed to the onset of melting in the shock wave. Figure 17 displays the phase diagram of molybdenum at high pressures. An inspection of this figure gives evidence that the description of the thermodynamic properties of shock-compressed molybdenum is trustworthy in the range of characteristics investigated, and the calculated pressure value of the onset of melting, $p = 3.85$ Mbar, coincides with the experimental result [104]. A comparison of the calculated shock Hugoniot of a heated liquid metal with the data of Ref. [105] also reveals their good agreement.

Measurements of molybdenum properties in isentropic unloading waves were taken in Refs [74, 106]. As suggested by calculated results, at the highest realized pressure of 2.3 Mbar for shock compression of crystalline molybdenum [74], the isentrope S_3 expands from the hot crystal domain to the two-phase liquid–crystal domain, while the two remaining isentropes (S_1 and S_2) dwell entirely in the solid phase domain. One can see from Fig. 18 that the data of Ref. [74] are accurately described by the EOS developed for molybdenum. In the experiments conducted in Ref. [106], due to the use of porous samples it was possible to realize liquid metal states with a higher entropy than in Ref. [74]. The calculated isentropes S_4 and S_5 experience kinks upon entry into the two-phase liquid–vapor domain at pressures of 5.48 and 1.67 kbar, which agrees nicely, to within the experimental error, with the $p-u$ dependence [106].

In the lower-density and moderate-pressure domain, measurements of the thermodynamic properties of molybdenum were made in experiments on isobaric expansion [107–111]. As is evident from Fig. 19, these data diverge by up to 20% in temperature and 10% in density, the data of Refs [107] and [111] being significantly different even in the solid phase domain. The scatter of estimates of the critical point is also quite broad: they range in density and temperature from 1 g cm^{-3} and 8000 K [112] to 3.1 g cm^{-3} and 19,720 K [106]. This is supposedly attributable to the nonstationarity of the measurement mode in the experiments of Refs [107–111], which leads to overrating the heat capacity and the slope of experimental isobars in density–temperature variables. The calculated position of the critical point at $p_c = 7.59$ kbar, $T_c = 10{,}180$ K, $V_c = 0.271\ \mathrm{cm}^3\ \mathrm{g}^{-1}$, and $s_c = 1.520\ \mathrm{J\ g}^{-1}\ \mathrm{K}^{-1}$ is in reasonable agreement with the estimates of Refs [109, 113], and the vaporization temperature $T_v = 4459$ K corresponds to a temperature of 4973 K given in reference book [114] and known to within 10%.

The EOS of molybdenum developed in the framework of this approach is validly used in numerical simulations of a broad range of problems of the physics of extreme states.

7. Conclusions

There is no way of reflecting the scope of Ya B Zeldovich's talent, fascination of his personality or his contribution to modern physics in one paper. We endeavored to show Ya B's influence and the impact of his ideas on a relatively narrow field — the physics of extreme states of matter. One can see that the fundamental ideas proposed by Ya B more than 50 years ago are now under development and underlie the advanced experimental and theoretical studies. This trait of Ya B Zeldovich's creative activity — to bring basic scientific ideas to embodiment in experiments or practical applications — persists in the works of his scientific school, his pupils, and their pupils.

Our country was lucky to have Yakov Borisovich. The 'father' of American hydrogen bomb E Teller would often say on meeting Soviet scientists (and even wrote about this in the foreword to the book on the physics of megagauss magnetic fields [12]) that the USSR was fortunate, because in our country there were such outstanding scientists as Ya B Zeldovich and L V Al'tshuler by the time of the onset of nuclear bomb research. But the American nuclear project was short of such people. In that project, there were first-rate experts in nuclear physics, but there were no outstanding experts in gas dynamics, especially those who knew both nuclear and gas-dynamic problems. The same thought in a conversation with V E F was expressed by H Bethe, who considered precisely the gas-dynamic part and the lack of corresponding experts in gas dynamics to be the most serious problems in the development of the American nuclear bomb.

Photo 2. At the L D Landau Institute for Theoretical Physics of the USSR Academy of Sciences in June 1986 (from left to right): Norris Keeler, Yakov Borisovich Zeldovich, and Vladimir Evgen'evich Fortov.

Once during a *Gordon Conference on High Pressure*, having initiated a discussion on the subject of not citing one of Ya B's studies on porous adiabats, V E F received a sincere reply from an American: "What is to be done? Once you have devised something worthwhile, it turns out that this has already been done and published by Zeldovich!"

In any event, by this time the third generation of scientists is discovering for itself the extensive creative work of Ya B, who is, unfortunately, not universally known abroad (although in many laboratories the book written by Ya B Zeldovich and Yu P Raizer [4] and the anniversary two-volume edition of Ya B's work [115, 116] lie in the most conspicuous place). Nevertheless, Ya B's influence on Western shock-wave science is extremely strong and fruitful. This was perfectly well stated by professor R N Keeler (on the left in Photo 2) in his paper "Some thoughts of an American scientist on the dynamic high-pressure work of Academician Ya B Zel'dovich" [38]. He observed, in particular, that "in the rich heritage of Academician Ya B Zel'dovich is a healthy and fruitful dynamic high-pressure research program in Russia."

References

1. Zel'dovich Ya B *Teoriya Udarnykh Voln i Vvedenie v Gazodinamiku* (The Theory of Shock Waves and Introduction to Gas Dynamics) (Moscow–Leningrad: Izd. AN SSSR, 1946)
2. Zeldovich Ia B, Kompaneets A S *Theory of Detonation* (New York: Academic Press, 1960); Translated from Russian: *Teoriya Detonatsii* (Moscow: Gostekhizdat, 1955)
3. Zel'dovich Ya B *Sov. Phys. JETP* **5** 1287 (1957); *Zh. Eksp. Teor. Fiz.* **32** 1577 (1957)
4. Zel'dovich Ya B, Raizer Yu P *Physics of Shock Waves and High-temperature Hydrodynamic Phenomena* (Mineola, N.Y.: Dover Publ., 2002); Translated from Russian: *Fizika Udarnykh Voln i Vysokotemperaturnykh Gidrodinamicheskikh Yavlenii* (Moscow: Fizmatlit, 2008)
5. Fortov V E *Ekstremal'nye Sostoyaniya Veshchestva* (Extreme States of Matter) (Moscow: Fizmatlit, 2009)
6. Al'tshuler L V *Sov. Phys. Usp.* **8** 52 (1965); *Usp. Fiz. Nauk* **85** 199 (1965)
7. Fortov V E *Extreme States of Matter on Earth and in the Cosmos* (Berlin: Springer, 2011)
8. Al'tshuler L V, Bakanova A A *Sov. Phys. Usp.* **11** 678 (1969); *Usp. Fiz. Nauk* **96** 193 (1968)
9. Fortov V E *Phys. Usp.* **50** 333 (2007); *Usp. Fiz. Nauk* **177** 347 (2007)
10. Fortov V E *Phys. Usp.* **52** 615 (2009); *Usp. Fiz. Nauk* **179** 653 (2009)
11. Fortov V E *Fizika Vysokikh Plotnostei Energii* (Physics of High Energy Densities) (Moscow: Fizmatlit, 2013)
12. Caldirola P, Knoepfel H (Eds) *Physics of High Energy Density* (New York: Academic Press, 1971)
13. Anisimov S I, Prokhorov A M, Fortov V E *Sov. Phys. Usp.* **27** 181 (1984); *Usp. Fiz. Nauk* **142** 395 (1984)
14. Fortov V E, Hoffmann D H H, Sharkov B Yu *Phys. Usp.* **51** 109 (2008); *Usp. Fiz. Nauk* **178** 113 (2008)
15. Dudin S V et al. *High Temp.* **48** 1 (2010); *Teplofiz. Vys. Temp.* **48** 3 (2010)
16. Landau L D, Zeldovich Ya B *Acta Physicochim. USSR* **18** 194 (1943); *Zh. Eksp. Teor. Fiz.* **14** 32 (1944)
17. Fortov V E, Krasnikov Yu G *Sov. Phys. JETP* **32** 897 (1971); *Zh. Eksp. Teor. Fiz.* **59** 1645 (1970)
18. Zeldovich Ya B, Todes O M *Acta Physicochim. USSR* **16** (1/2) 26 (1942); *Zh. Eksp. Teor. Fiz.* **10** 1441 (1940)
19. Dzyabura V, Zaghoo M, Silvera I F *Proc. Natl. Acad. Sci. USA* **110** 8040 (2013)
20. Fortov V E et al. *JETP* **97** 259 (2003); *Zh. Eksp. Teor. Fiz.* **124** 288 (2003)

21. Fortov V E, Mintsev V B *Phys. Rev. Lett.* **111** 125004 (2013)
22. Rubakov V A *Phys. Usp.* **55** 949 (2012); *Usp. Fiz. Nauk* **182** 1017 (2012)
23. Fortov V E, Khrapak A G, Iakubov I T *Fizika Neideal'noi Plazmy* (The Physics of Nonideal Plasma) (Moscow: Fizmatlit, 2004)
24. Henderson D (Ed.) *Frontiers in High Energy Density Physics* (Washington, D.C.: National Academies Press, 2003)
25. Landau L D, Lifshitz E M *Statistical Physics* Vol. 1 (Oxford: Pergamon Press, 1980); Translated from Russian: *Statisticheskaya Fizika* Pt. 1 (Moscow: Fizmatlit, 2001)
26. Fortov V E, Iakubov I T, Khrapak A G *Physics of Strongly Coupled Plasma* (Oxford: Oxford Univ. Press, 2006)
27. Ginzburg V L *Phys. Usp.* **47** 1155 (2004); *Usp. Fiz. Nauk* **174** 1240 (2004)
28. Hemley R J, Ashcroft N W *Phys. Today* **51** (8) 26 (1998)
29. Zasov A V, Postnov K A *Obshchaya Astrofizika* (General Astrophysics) (Fryazino: Vek 2, 2006)
30. Drake R P *High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics* (Berlin: Springer, 2006)
31. Shatskii A A, Novikov I D, Kardashev N S *Phys. Usp.* **51** 457 (2008); *Usp. Fiz. Nauk* **178** 481 (2008)
32. Potekhin A Yu *Phys. Usp.* **53** 1235 (2010); *Usp. Fiz. Nauk* **180** 1279 (2010)
33. Shakura N I et al. *Phys. Usp.* **56** 321 (2013); *Usp. Fiz. Nauk* **183** 337 (2013)
34. Beskin V S, Istomin Ya N, Philippov A A *Phys. Usp.* **56** 164 (2013); *Usp. Fiz. Nauk* **183** 179 (2013)
35. Babichev E O, Dokuchaev V I, Eroshenko Yu N *Phys. Usp.* **56** 1155 (2013); *Usp. Fiz. Nauk* **183** 1257 (2013)
36. Bridgman P W *Rev. Mod. Phys.* **18** 1 (1946); *Usp. Fiz. Nauk* **31** 53 (1947); *Usp. Fiz. Nauk* **31** 210 (1947); *Usp. Fiz. Nauk* **31** 346 (1947)
37. Rakovskii A V *Usp. Fiz. Nauk* **1** 39 (1918); *Usp. Fiz. Nauk* **1** 108 (1918); *Usp. Fiz. Nauk* **1** 182 (1918)
38. Keeler R N *Phys. Usp.* **38** 559 (1995); *Usp. Fiz. Nauk* **165** 595 (1995)
39. Bridgman P W, in *Solids under Pressure* (Eds W Paul, D M Warschauer) (New York: McGraw-Hill, 1963); Translated into Russian: *Tverdye Tela pod Vysokim Davleniem* (Eds W Paul, D M Warschauer) (Moscow: Mir, 1966) p. 11
40. Al'tshuler L V, Zel'dovich Ya B, Styazhkin Yu M *Phys. Usp.* **40** 101 (1997); *Usp. Fiz. Nauk* **167** 107 (1997)
41. Zababakhin E I *Sov. Phys. Usp.* **8** 295 (1965); *Usp. Fiz. Nauk* **85** 721 (1965)
42. Trunin R F *Phys. Usp.* **37** 1123 (1994); *Usp. Fiz. Nauk* **164** 1215 (1994)
43. Al'tshuler L V et al. *Phys. Usp.* **39** 539 (1996); *Usp. Fiz. Nauk* **166** 575 (1996)
44. Funtikov A I *Phys. Usp.* **40** 1067 (1997); *Usp. Fiz. Nauk* **167** 1119 (1997)
45. Al'tshuler L V et al. *Phys. Usp.* **42** 261 (1999); *Usp. Fiz. Nauk* **169** 323 (1999)
46. Trunin R F *Phys. Usp.* **44** 371 (2001); *Usp. Fiz. Nauk* **171** 387 (2001)
47. Ilkaev R I *Phys. Usp.* **54** 387 (2011); *Usp. Fiz. Nauk* **181** 405 (2011)
48. Trunin R F *Phys. Usp.* **54** 397 (2011); *Usp. Fiz. Nauk* **181** 416 (2011)
49. Podurets A M *Phys. Usp.* **54** 408 (2011); *Usp. Fiz. Nauk* **181** 427 (2011)
50. Fermi E *Rend. Accad. Naz. Lincei* **6** 602 (1927)
51. Fortov V E *J. Appl. Mech. Tech. Phys.* **13** 894 (1972); *Zh. Prikl. Mekh. Tekh. Fiz.* (6) 156 (1972)
52. Krupnikov K K, Brazhnik M I, Krupnikova V P *Sov. Phys. JETP* **15** 470 (1962); *Zh. Eksp. Teor. Fiz.* **42** 675 (1962)
53. Kormer S B et al. *Sov. Phys. JETP* **15** 477 (1962); *Zh. Eksp. Teor. Fiz.* **42** 686 (1962)
54. Alekseev Yu L, Ratnikov V P, Rybakov A P *J. Appl. Mech. Tech. Phys.* **12** 257 (1971); *Zh. Prikl. Mekh. Tekh. Fiz.* (2) 101 (1971)
55. Bakanova A A, Dudoladov I P, Sutulov Yu N *J. Appl. Mech. Tech. Phys.* **15** 241 (1974); *Zh. Prikl. Mekh. Tekh. Fiz.* (2) 117 (1974)
56. Zubarev V N et al., in *Detonatsiya* (Detonation) (Ed. A N Dremin) (Chernogolovka: Otdel. IKhF AN SSSR, 1978) p. 61
57. Al'tshuler L V et al. *Sov. Phys. JETP* **51** 373 (1980); *Zh. Eksp. Teor. Fiz.* **78** 741 (1980)
58. Zhernokletov M V, Zubarev V N, Sutulov Yu N *J. Appl. Mech. Tech. Phys.* **25** 107 (1984); *Zh. Prikl. Mekh. Tekh. Fiz.* (1) 119 (1984)
59. Glushak B L et al. *Sov. Phys. JETP* **69** 739 (1989); *Zh. Eksp. Teor. Fiz.* **96** 1301 (1989)
60. Trunin R F et al. *Sov. Phys. JETP* **69** 580 (1989); *Zh. Eksp. Teor. Fiz.* **96** 1024 (1989)
61. Trunin R F et al. *Sov. Phys. JETP* **68** 356 (1989); *Zh. Eksp. Teor. Fiz.* **95** 631 (1989)
62. Trunin R F, Simakov G V *JETP* **76** 1090 (1993); *Zh. Eksp. Teor. Fiz.* **103** 2180 (1993)
63. Gryaznov V K et al. *JETP* **87** 678 (1998); *Zh. Eksp. Teor. Fiz.* **114** 1242 (1998)
64. Bushman et al. *JETP Lett.* **58** 620 (1993); *Pis'ma Zh. Eksp. Teor. Fiz.* **58** 640 (1993)
65. Funtikov A I *High Temp.* **36** 384 (1998); *Teplofiz. Vys. Temp.* **36** 406 (1998)
66. Trunin R F, Panov N V *High Temp.* **38** 728 (2000); *Teplofiz. Vys. Temp.* **38** 754 (2000)
67. Gudarenko L F et al. *High Temp.* **38** 413 (2000); *Teplofiz. Vys. Temp.* **38** 437 (2000)
68. Trunin R F, Simakov G V, Panov N V *High Temp.* **39** 401 (2001); *Teplofiz. Vys. Temp.* **39** 430 (2001)
69. Lomonosov I V *Laser Part. Beams* **25** 567 (2007)
70. Volkov K V, Sibilev V A *J. Appl. Mech. Tech. Phys.* **22** 551 (1981); *Zh. Prikl. Mekh. Tekh. Fiz.* (4) 125 (1981)
71. Trunin R F et al. *Teplofiz. Vys. Temp.* **33** 222 (1995)
72. Al'tshuler L V et al. *Sov. Phys. JETP* **46** 980 (1977); *Zh. Eksp. Teor. Fiz.* **73** 1866 (1977)
73. Bakanova A A et al. *J. Appl. Mech. Tech. Phys.* **24** 204 (1983); *Zh. Prikl. Mekh. Tekh. Fiz.* (2) 76 (1983)
74. Zhernokletov M V et al. *Teplofiz. Vys. Temp.* **33** 40 (1995)
75. Trunin R F et al. *Eksperimental'nye Dannye po Udarno-Volnovomu Szhatiyu i Adiabaticheskomu Rasshireniyu Kondensirovannykh Veshchestv* (Experimental Data on the Shock-Wave Compression and Adiabatic Expansion of Condensed Substances) (Ed. R F Trunin) (Sarov: RFYaTs–VNIIEF, 2001)
76. Knudson M D, Asay J R, Deeney C *J. Appl. Phys.* **97** 073514 (2005)
77. Kvitov S V et al. *JETP Lett.* **53** 353 (1991); *Pis'ma Zh. Eksp. Teor. Fiz.* **53** 338 (1991)
78. Gryaznov V K et al. *Sov. Phys. JETP* **51** 288 (1980); *Zh. Eksp. Teor. Fiz.* **78** 573 (1980)
79. Gryaznov V K, Iosilevskii I L, Fortov V E *Pis'ma Zh. Tekh. Fiz.* **22** 1376 (1982)
80. Gryaznov V K, Fortov V E *Teplofiz. Vys. Temp.* **25** 1208 (1987)
81. Ageev V G et al. *JETP Lett.* **48** 659 (1988); *Pis'ma Zh. Eksp. Teor. Fiz.* **48** 608 (1988)
82. Zhernokletov M V *High Temp.* **36** 214 (1998); *Teplofiz. Vys. Temp.* **36** 231 (1998)
83. Kulish et al. *JETP Lett.* **94** 101 (2011); *Pis'ma Zh. Eksp. Teor. Fiz.* **94** 105 (2011)
84. Ternovoi V Ya et al. *AIP Conf. Proc.* **505** 189 (2000)
85. Khishchenko K V et al. *High Temp. High Press.* **37** 291 (2008)
86. Bushman A V et al. *Phys. Dokl.* **38** 165 (1993); *Dokl. Ross. Akad. Nauk* **329** 581 (1993)
87. Bushman A V et al. *JETP* **82** 895 (1996); *Zh. Eksp. Teor. Fiz.* **109** 1662 (1996)
88. Khishchenko K V, Zhernokletov M V, Lomonosov I V, Sutulov Yu N *Tech. Phys.* **50** 197 (2005); *Zh. Tekh. Fiz.* **75** (2) 57 (2005)
89. Hoffmann D H H et al. *Phys. Plasmas* **9** 3651 (2002)
90. Fortov V E, Sharkov B Yu, Stöcker H *Phys. Usp.* **55** 582 (2012); *Usp. Fiz. Nauk* **182** 621 (2012)
91. Fortov V E *Uravneniya Sostoyaniya Veshchestva: ot Ideal'nogo Gaza do Kvark-Glyuonnoi Plazmy* (Equations of State of Substances: from Ideal Gas to Quark-Gluon Plasma) (Moscow: Fizmatlit, 2012)
92. Kerley G I *Int. J. Impact Eng.* **5** 441 (1987)
93. More R M et al. *Phys. Fluids* **31** 3059 (1988)
94. Young D A, Corey E M *J. Appl. Phys.* **78** 3748 (1995)
95. Bushman A V, Kanel G I, Ni A L, Fortov V E *Thermophysics and Dynamics of Intense Pulse Loadings* (London: Taylor & Francis, 1993)
96. Bushman A V, Lomonosov I V, Fortov V E *Uravneniya Sostoyaniya Metallov pri Vysokikh Plotnostyakh Energii* (Equations of State of Metals at High Energy Densities) (Chernogolovka: IKhFCh RAN, 1992)
97. Fortov V E, Lomonosov I V *Pure Appl. Chem.* **69** 893 (1997)

98. Val'ko V V et al., in *Fizika Yadernogo Vzryva* (Physics of Nuclear Explosion) Vol. 2 *Deistvie Vzryva* (Action of the Explosion) (Moscow: Fizmatlit, 2010) p. 140
99. Fortov V E, Lomonosov I V *Open Plasma Phys. J.* **3** 122 (2010)
100. Kalitkin N N, Kuz'mina L V, Preprint No. 35 (Moscow: Keldysh Institute of Applied Mathematics, Academy of Sciences USSR, 1975)
101. Kormer S B, Urlin V D, Popova L T *Sov. Phys. Solid State* **3** 1547 (1962); *Fiz. Tverd. Tela* **3** 2131 (1961)
102. Gathers G R, Shaner J W, Hodson W M *High Temp. High Press.* **11** 529 (1979)
103. Guillermet F A *Int. J. Thermophys.* **6** 367 (1985)
104. Hixson R S et al. *Phys. Rev. Lett.* **62** 637 (1989)
105. Duffy T S, Ahrens T J *J. Appl. Phys.* **76** 835 (1994)
106. Zhernokletov M V, Medvedev A B, Simakov G V *Khim. Fiz.* **14** (2–3) 49 (1995)
107. Shaner J W, Gathers R G, Minichino C *High Temp. High Press.* **9** 331 (1977)
108. Seydel U, Kitzel W *J. Phys. F Met. Phys.* **9** L153 (1979)
109. Gathers G R *Int. J. Thermophys.* **4** 209 (1983)
110. Pottlacher G, Kaschnitz E, Jager H *J. Phys. Condens. Matter* **3** 5783 (1991)
111. Hixson R S, Winkler M A *Int. J. Thermophys.* **13** 477 (1992)
112. Young D, Report UCRL-52352 (Livermore: Lawrence Livermore Lab., 1977)
113. Seydel U, Fucke W *J. Phys. F Met. Phys.* **8** L157 (1978)
114. Kikoin I K (Ed.) *Tablitsy Fizicheskikh Velichin* Spravochnik (Physical Data Tables. Reference Book) (Moscow: Energoatomizdat, 1976)
115. Zeldovich Ya B *Chemical Physics and Hydrodynamics*: *Selected Works of Yakov Borisovich Zeldovich* (Eds J P Ostriker, G I Barenblatt, R A Sunyaev) (Princeton, N.J.: Princeton Univ. Press, 1993); Translated from Russian: *Khimicheskaya Fizika i Gidrodinamika*: *Izbrannye Trudy* (Ed. Yu B Khariton) (Moscow: Nauka, 1984)
116. Zeldovich Ya B *Particles, Nuclei, and the Universe*: *Selected Works of Yakov Borisovich Zeldovich* (Eds J P Ostriker, G I Barenblatt, R A Sunyaev) (Princeton, N.J.: Princeton Univ. Press, 1993); Translated from Russian: *Chastitsy, Yadra, Vselennaya*: *Izbrannye Trudy* (Ed. Yu B Khariton) (Moscow: Nauka, 1985)