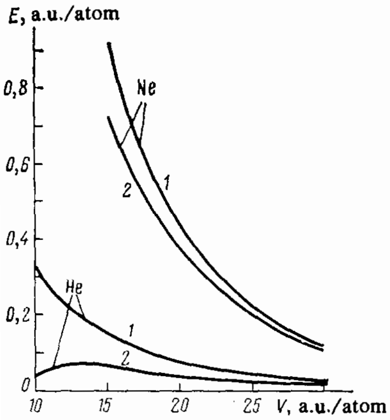

FIG. 3. Energy of fcc crystals of He and Ne as a function of the specific volume. 1) Pair-interaction approximation; 2) including three-particle interactions.

interactions play an important role in molecular hydrogen was also arrived at in Ref. 13 on the basis of an analysis of experimental data on dynamic compression.

The light inert gases—helium and neon—exhibit analogous behavior in the megabar range.[14] Calculations based on the cluster expansion of the energy of fcc lattices show that the nonadditive three-particle interaction of He and Ne molecules appreciably lowers the energy of the crystal as compared with the pair-interaction approximation (Fig. 3). This leads, correspondingly, to lower pressures.

[1)]We call attention to the fact that the contribution of linear three-particle clusters to the energy is negligibly small. The main contribution is linked to structures which are apparently not realized in the scattering experiments from which the interparticle potentials are often determined.

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L. V. Al'tshuler. *Results of and prospects for experimental studies of extremal states of matter.* The equations of state for extremal states of matter with high energy density are found from the result of static and dynamic experiments and their extrapolations to the periphery of phase diagrams, where simple theoretical models constructed from first principles are valid.

The basic thermodynamic characteristics of compressed and heated bodies are determined by the potential curves of "cold" interaction of particles and "Grüneisen functions," which reflect the thermal elasticity of matter. The experimental search for these dependences over a wide range of temperatures and densities was made possible by the use of strong shock waves as a tool in the physical studies.[1,2] Dynamic methods, developed independently in the Soviet Union and in the USA right after World War II are based on obtaining and recording states arising for short periods of time in sample targets struck by impactors. The measured quantities in shock-wave experiments are the velocity of the shock wave in the target and the velocity of the matter behind the wave front, determined from the velocity of the impactor. Through the equations expressing the conservation laws the kinematic characteristics of the wave determine the thermodynamic parameters of the compressed material: the pressure, density, and specific internal energy acquired from the impact. The measurements performed with different shock-wave velocities establish on the phase diagrams the trajectories characteristic shock-compression trajectories—the Hugoniot adiabats—with known values of the thermodynamic quantities.

Using the method of shock waves, by the beginning of the 1960s, pressures of the order of 1 TPa, which represent the upper limit of absolute laboratory measurements of the dynamic compressibility, were achieved in the Soviet Union using explosive devices which smoothly accelerated iron impactors up to velocities of ~ 15–18 km/sec. Half of this range has now been achieved in the USA, where systematic studies are performed with a two-stage light-gas cannon, which imparts a velocity of up to 8.5 km/sec to a tantalum impactor.[3]

Further progress toward the limits of the theoretical description has been achieved in experiments with shock waves in the near zone of strong undeground explosions. Under these conditions, with the help of γ emitters built into an aluminum sample, in Ref. 4 wave and mass velocities were measured and the compressibility of aluminum at 1 TPa was determined. A different, less accurate method was used in Ref. 5 to obtain the parameters of the shock-compression of molybdenum at 2 TPa. The main result[6–8] of the studies in the tera-Pascal pressure range was the determination of the comparative compressibility of many metals. In the experiments set up for these purposes, the velocities of the shock wave were recorded as the wave passed through successive layers of different metals. The interpretation of these experiments requires knowledge of the shock adiabat of one of the metals. In studies carried out in the Soviet

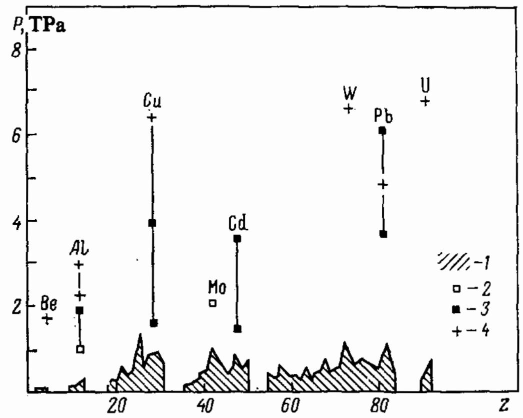

FIG. 1. The ranges of absolute and comparative measurements of the dynamic compressibility of the elements. a) Absolute laboratory measurements, 2) same under conditions of strong underground explosions[4,5]; 3) comparative measurements based on the data in Refs. 6 and 7; 4) same from Ref. 8.

Union, the standard material consisted of iron with an interpolation shock adiabat connecting the upper points of the laboratory experiment and quantum-statistical calculations. In studies abroad[8] the experiments were interpreted with the use of a computed quantum-mechanical adiabat for molybdenum.

The histogram in Fig. 1 illustrates the scope of the dynamic studies performed to determine the absolute and relative compressibility of the elements. Estimates of the compressibility of aluminum under gigabar pressures, obtained by Volkov *et al.*,[4] fall outside the scope of the graph.

Dynamic studies performed during the last decades have provided unique information on the potential interaction curves of atoms in metals,[9–11] liquids,[12] and inert gases[13]; on the compressibility of minerals under the pressures of the earth's lower mantel[14]; on the temperaturs of dielectrics behind shock-wave fronts[15]; and, on the gradual approach of dielectrics to a metallic state.[16,17] Numerous and previously unknown electronic transitions were discovered[18] and the parameters of the detonation products were determined. The results of the dynamic studies formed the criteria for theoretical models and provided reference curves of the dynamic and static compressibility for high-pressure metrology.

At the initiative of and following the program oulined by Ya. B. Zel'dovich, from the first use of dynamic methods Soviet researchers directed their efforts toward determining over a wide range the parameters of the thermal components *of the equations of state.* To this end, the sound velocities behind the shock-wave fronts were measured for a series of metals,[2] and their porous adiabats were recorded[19,20] with low initial density of the samples and isentropic expansion from high energy states.[21] The results of a comprehensive study of copper up to pressures of 2.5 TPa and in the range of doubled and halved density are shown in Fig. 2. The good agreement between the data on the compressibility of copper obtained in Ref. 9 in 1962 and a recently published foreign study[3] is interesting. Up to 0.2 TPa the adiabat of copper with normal initial density, after the thermal pressures are

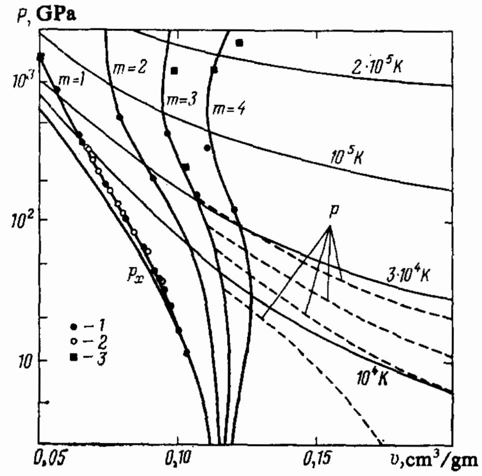

FIG. 2. Shock and isentropic compressibility of copper.[21] m corresponds to the Hugoniot adiabats for different degree of porosity $m = 1, 2, 3, 4$; p_x is the isotherm at $T = 0$ K. p_x is the isotherm at $T = 0$ K. $p = p_s$ are the isentropes. 1) Data from Refs. 9 and 20; 2) Ref. 3; 3) results of comparative measurements.[22]

subtracted out, uniquely determines the potential curve for cold compression p_x. The unique configuration of the porous adiabats obtained in Refs. 20 and 22 reflects the variation of the thermal elasticity with temperature: it decreases at 0.4 TPa and then increases at pressures of the order of 2 TPa. New information on the thermodynamics of copper at a density less than the normal density was obtained in Refs. 21 using the method of isentropic expansion.

The present status of the study of extremal states of metals is also illustrated by the phase diagram of lead (Fig. 3), constructed on a logarithmic scale in the plane defined by the density and the specific internal energy. As the graphs show, the position of the shock adiabat of lead under extremal pressures of 2–5 TPa is determined with high accuracy in the comparative experiments. This is indicated by the consistency of the data[7,8] interpreted using different methods. As in the case of copper, information on the ratio of the

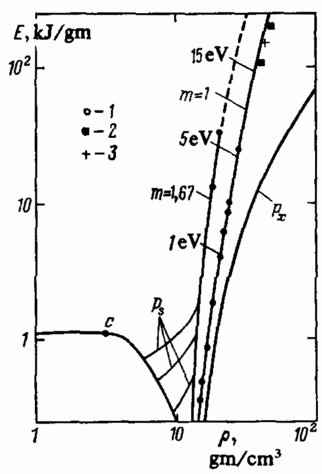

FIG. 3. Phase diagram of lead. m, p_x, and p_s are defined in the same way as in Fig. 2. c is the critical state. 1) Laboratory measurements from Refs. 9 and 20; 2) data from comparative measurements from Ref. 7; 3) same from Ref. 8.

thermal pressure and the thermal energy was obtained in experiments on the compression of porous samples and by recording their subsequent expansion.

Both lead and other metals, which were not included in the experimental studies, retained high energy states of a strongly nonideal plasma, occupying on the abscissa axis a range of densities covering two orders of magnitude: from hundreths of a gram to several grams.

The experimental study of these states by dynamic methods in their traditional and modified variants, as well as the construction of adequate theoretical models for them, is one of the basic directions of research in the physics of high energy densities.[23]

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V. E. Fortov. *Equation of state of a nonideal plasma for extreme values of the parameters.* The thermodynamic properties of thermally ionized plasma can be calculated reliably in limiting cases of ultrahigh temperatures and pressures, when the classical (Debye-Hückel) and quasiclassical (Thomas-Fermi) approximations to the self-consistent field method are applicable.[1] The region of compressed and heated solid and liquid is realized in static[2] and dynamic[3] experiments. In the intermediate region of parameters, between the condensed state and the ideal gas, a dense plasma with strong interparticle interaction arises, and this impedes the use of theoretical methods[4] and urgently requires experimental studies.[5,6]

Two basic modifications of dynamic methods are used to study an ideal plasma experimentally[3–5]: shock-wave or adiabatic compression of inert gases and vapors of alkali metals, as well as adiabatic expansion of metals which are precompressed and preheated by strong shock waves. The experiments on shock-wave compression of dense inert gases (the initial state (1) in Fig. 1) made it possible to obtain plasma under high pressures $P \lesssim 180$ kbar and at high temperatures $T \lesssim 10^5$ K, where fully developed ionization $n_e \lesssim 10^{23}$ cw^{-3} is realized with densities of up to 4.5 g/cm^3, exceeding by a factor of 1.5 the crystallographic density of xenon.[8]

Under these conditions the plasma nonideality parameter

$$\Gamma = \frac{e^2 k\rho}{kT} = \frac{4\pi e^3 n_e^{1/2}}{(kT)^{3/2}},$$

reaches 10, and the electron gas is nearly degenerate:

$$n_e\lambda_e^3 = n_e\left(\frac{\hbar^2}{2\pi mkT}\right)^{3/2} \sim 0.6.$$

This region of parameters was studied with the help of linear explosive shock tubes and explosive projectile devices as a result of both single compression (state 2 in Fig. 1) and two-fold compression and with the use of the effects of shaping (state 3). Under these conditions it is possible to measure the caloric and thermal equations of state, the electrical conductivity, and the coefficients of absorption and reflection of visible light from the shock-compressed plasma.[5,6] It is im-

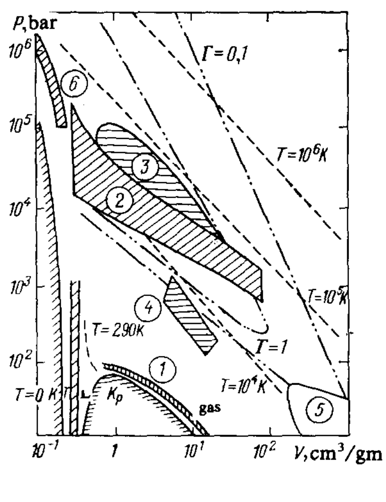

FIG. 1. Phase diagram of xenon. T, K—cold-compression curve, K_p is the critical point. The dashed curves are the isotherms and the dot-dashed curves are curves of constant degree of nonideality Γ. the remaining notation is deifned in the text.