Springer Series in Materials Science

Volume 216

The Springer Series in Materials Science covers the complete spectrum of materials physics, including fundamental principles, physical properties, materials theory and design. Recognizing the increasing importance of materials science in future device technologies, the book titles in this series reflect the state-of-the-art in understanding and controlling the structure and properties of all important classes of materials.

More information about this series at http://www.springer.com/series/856

Vladimir E. Fortov

Extreme States of Matter

High Energy Density Physics

Second Edition

Springer

Prof. Vladimir E. Fortov
President of the Russian Academy of Sciences
Joint Institute for High Temperatures
Moscow, Russia

Translated by Prof. Eugene N. Ragozin
Desk editor Dr. Valery G. Sultanov
Managing editor Dr. Maria S. Aksenteva

Based on updated and integrated translations of "Ekstremal'nye sostoyaniya veshchestva" (Fizmatlit, Moscow 2009), [English translation: Extreme States of Matter (Springer, Berlin-Heidelberg 2011)] and "Fizika Vysokikh Plotnostei Energii" (High Energy Density Physics) (Fizmatlit, Moscow 2012)

ISSN 0933-033X ISSN 2196-2812 (electronic)
Springer Series in Materials Science
ISBN 978-3-319-18952-9 ISBN 978-3-319-18953-6 (eBook)
DOI 10.1007/978-3-319-18953-6

Library of Congress Control Number: 2015959700

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

...but thou hast ordered all things in measure and number and weight

The Wisdom of Solomon 11:20

Preface to the First Edition

This book is concerned with the physical properties of matter and the diverse processes that occur in nature at ultrahigh energy densities, which correspond to extreme pressures and temperatures. It is based on the lecture course I hold at the Moscow Institute of Physics and Technology, as well as reviews and invited papers written for scientific conferences and symposia.

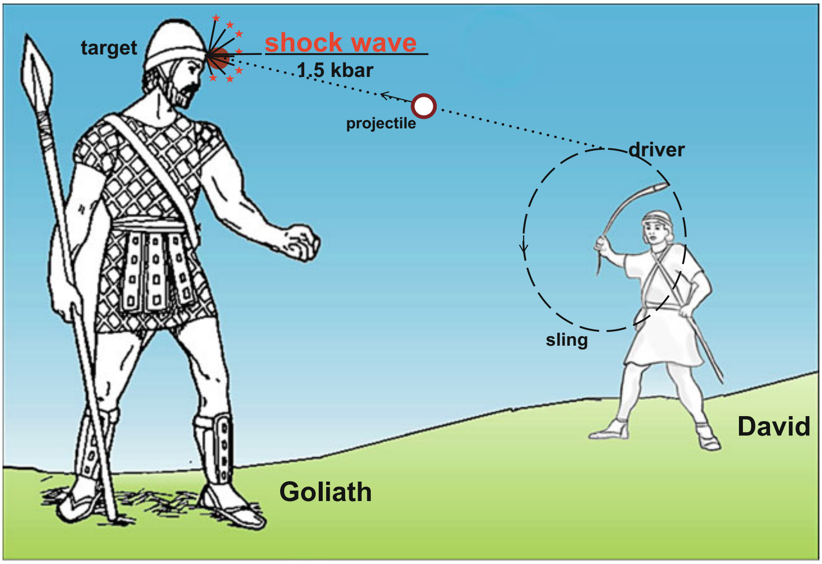

Fig. 1 The battle between David and Goliath [1]

Interest in the physics of extreme states has always been strong, owing to the natural desire of humans to achieve more and to operate with record parameters, as well as owing to the wealth of applications to astrophysics, energy production, and defense. It was indeed military application that fostered the first successful experiment involving extreme states, which was conducted more than 3000 years ago – during the battle between David and Goliath (Fig. 1). According to the Old Testament [1], the high-velocity impact of a stone, which was shot from David's sling, on Goliath's head killed him. It gave rise to a shock wave in Goliath's head with an amplitude pressure of ≈ 1.5 kbar, which was more than twice the strength of Goliath's frontal bone and determined the outcome of the duel, to the great joy of the army and people of Israel. Discovered to be successful at that time, this scheme of action serves as the basis for all subsequent experiments in the area of dynamic high-energy-density physics.

The application of more powerful and highly sophisticated energy cumulation systems – chemical and nuclear explosives, powder, light-gas, and electrodynamic "guns", charged-particle fluxes, laser and X-ray radiation – has enabled the velocity of "thrown" projectiles to be raised by three or four orders of magnitude, since the time of David, and the pressure in the shock wave by six to eight orders of magnitude, thereby reaching the megabar-gigabar pressure range and "nuclear" energy densities in substances.

In the 20th century, mainstream high-energy-density physics was closely related to the arrival of the atomic and space era in our civilization. In nuclear charges, the high energy densities generated by intense shock waves serve to initiate chain nuclear reactions in compressed nuclear fuel. In thermonuclear charges and microtargets for controlled fusion, high-energy states are the main instrument for compressing and heating the thermonuclear fuel and initiating thermonuclear reactions in it.

Recently, interest in the science of extreme states has been rekindled as a result of the emergence of new experimental techniques for the generation of high-energy states in terrestrial conditions as well as intriguing new observational astrophysical data obtained by modern-generation ground-based and space telescopes operating at different wavelengths and by unmanned space stations.

Although the limiting pressures in laboratory plasmas so far differ from the maximum astrophysical values by 20–30 orders of magnitude, this gap is rapidly shrinking. The physical processes in a laboratory and in space quite frequently exhibit an amazing diversity and, at the same time, striking similarities, thereby testifying, at the least, to the uniformity of the physical principles of the behavior of matter over an extremely broad range of pressures (42 orders of magnitude) and temperatures (up to 10^{13} K).

However, as pointed out by Voltaire, "... in nature this phenomenon is perfectly natural and commonplace. The domains of some rulers in Germany and Italy, which can be circled in about a half hour, when compared with the empires of Turkey, Moscow, or China, give only a faint idea of the remarkable contrasts that are hidden in all of nature" (Voltaire, *Le Micromégas*, Paris 1752) [3].

It is significant that the range of technical problems related to the physics of extreme states is progressively broadening along with the range of the fundamental ones. These states of matter underlie the operation of pulsed thermonuclear reactors with inertial confinement of the hot plasma, high-power explosive-driven magnetic generators, power installations and rocket propulsors with gas-phase nuclear reactors, plasmachemical and microwave reactors, plasmatrons, and high-power sources of optical radiation and X-rays. In the energy installations of the future, strongly compressed and heated plasmas will be employed as the working medium, like water vapor in modern thermal power stations.

Extreme states emerge when a substance is subjected to intense shock, detonation, or electroexplosion waves, concentrated laser radiation, electron and ion beams, in powerful chemical and nuclear explosions, in the pulsed vaporization of liners in pinches and magnetic cumulation generators, in the hypersonic motion of bodies in dense planetary atmospheres, in high-velocity impacts, and in many other situations characterized by ultrahigh pressures and temperatures. The physics of near-electrode, contact, and electroexplosion processes in vacuum breakdown is intimately related to the high-energy plasma that defines the operation of high-power pulsed accelerators, microwave radiation generators, and plasma switches.

High energy densities determine the behavior of matter in a vast domain of the phase diagram that occupies the range from a solid and a fluid to a neutral gas, covers the phase boundaries of melting and boiling, and also the metal-dielectric transition domain. The metal–dielectric transition problem has been much explored in experiments involving the multiple (quasi-isentropic) shock-wave compression of dielectrics, their metallization, and the recently discovered plasma phase transitions in the megabar pressure range, as well as dielectrization of strongly compressed simple metals.

Scientific interest in high-energy plasmas has also been rekindled along with pragmatic interest, because the great bulk of matter in the universe is in precisely this exotic state. For about 95% of the mass (neglecting dark matter), according to modern estimates, is the plasma of ordinary and neutron stars, pulsars, black holes, and giant planets of the solar system, as well as the recently discovered hundreds of planets beyond the solar system.

Prior to becoming a star, the matter of the universe experiences the most diverse physical transformations: from quarks and elementary particles to complex molecules and again to atoms and particles; from relativistic energies to absolute zero and again to the state of high-energy-density plasma; from enormous densities to ultrahigh vacuum and again to the densities of atomic nuclei and quarks. And so our fundamental knowledge of the structure, evolution, and history of the universe is directly dependent on our understanding of the behavior of matter in all of its transformations up to ultrahigh energy densities, which forms not only specific physical models, but also the world-outlook of modern natural science because, by steadily increasing the high energy densities attainable by investigations on Earth and in space, we delve into the past, using a "time machine", looking for the singular conditions of the Big Bang – the instant of the universe's inception $\approx$1.5 billion years ago.

Today we can clearly see that the study of matter in extreme states is one of the "hottest" and most rapidly developing basic scientific disciplines, situated at the interface between plasma physics, nonlinear optics, condensed-matter physics, nuclear, atomic and molecular physics, relativistic and magnetic hydrodynamics, involving a wealth of compression- and heating-stimulated physical effects and a constantly widening variety of objects and states in which the plasma nonideality is critically important. Despite the extraordinary diversity of the objects and experimental and astrophysical situations, they all share the common property that high energy densities play a decisive role in their physical behavior.

These circumstances are a permanent steadfast incentive for intensive theoretical and experimental investigations, which have recently resulted in a great body of new and, most important, reliable information about the thermodynamic, structural, gasdynamic, optical, electrophysical, and transport properties of matter under extreme conditions. These specific data are contained in a massive flow of original publications, some of which are not easily accessible to Russian scientists, especially young ones.

This book attempts to systematize, generalize, and set forth from a unified viewpoint the theoretical and experimental material related to this new realm of science, and to show, following Titus Lucretius Carus, "Thus from the mixture of the elements there emerge infinite multitudes of creatures, which are Strange and highly diversified in appearance" (Titus Lucretius Carus) [2]. In it I endeavor to discuss the maximally broad range of problems related to high-energy-density physics. That is why many interesting astrophysical, laser, and nuclear-physical problems as well as technical applications are briefly outlined and the reader is referred to original papers and monographs. In doing this, I did not aim to include everything known about extreme states to date. Emphasis was placed on the issues which appeared to be most interesting to me and which I happened to work on directly. Realizing that the material touched upon in this book will steadily broaden, become defined more precisely, and inevitably become obsolete owing to the extremely rapid development of high-energy-density physics, I would be thankful to readers who send me critical remarks and suggestions.

It is hoped that this book will be beneficial to a wide readership of scientists, postgraduates, and students in the natural sciences by offering them access to original papers and being a helpful guide through the exciting problems of modern Extreme State Physics.

In the preparation of the manuscript I benefited from the assistance, stimulating discussions, and advice of Yu.Yu. Balega, N.E. Andreev, A.Ya. Faenov, S.I. Blinnikov, M.B. Kozintsova, A.N. Starostin, V.S. Imshennik, I.L. Iosilevskii, N.S. Kardashev, V.G. Sultanov, A.N. Sissiakian, B.Yu. Sharkov, and V.A. Yakovleva, to whom I express my sincere gratitude.

Abramtsevo, Russia Vladimir Fortov
May 2009

References

1. Bible. Old Testament, 1 Samuel, 17: 34, 40, 43, 48–51
2. Lucretius: The Nature of Things. Penguin, London (2007)
3. Voltaire: Micromégas and Other Short Fiction. Penguin, London (2002)

Preface to the Second Edition

Dear reader!

The monograph before you is concerned with the diverse physical phenomena occurring in matter in which there is an extremely high energy density, generating in turn ultrahigh pressures and temperatures.

This second edition results from a thorough revision of the first edition [1], which was published in English in 2011, together with the addition of material from another monograph [2], published in Russian in 2012. All the material included herein has been substantially updated and the subject matter of the book considerably expanded by including recent experimental results as well as new theoretical approaches and models. This is also reflected in the new subtitle, which corresponds to the contents more adequately.

This book will hopefully arouse readers' curiosity and be helpful to scientists, post-graduates, and students interested in this fascinating realm of modern physics, and especially to those who have decided to make this field the subject of their future research activities.

Abramtsevo, Moscow
April 2015

Vladimir E. Fortov

References

1. Fortov, V.E.: Ekstremal'nye sostoyaniya veshchestva (Extreme States of Matter). Fizmatlit, Moscow (2009) [Translated into English: Extreme States of Matter. Series: The Frontiers Collection. Springer, Berlin/Heidelberg (2011)]
2. Fortov, V.E.: Fizika Vysokikh Plotnostei Energii (High Energy Density Physics). Fizmatlit, Moscow (2012)

Contents