Physics and Biology

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Preface

This small book is intended for those readers who want to be acquainted with some important problems in the contemporary natural sciences that are related to biophysics. As a result of the great developments in biology, physics, and chemistry, there has begun the building of biological physics, i.e., the science that studies life from the viewpoint of the laws and methods of experimental and theoretical physics. This basis has proved to be reliable: biophysics has already added to the understanding of a series of biological phenomena, and it has led to discoveries that are important for both theory and practice. On the one hand biophysics leads to the development of theoretical biology and on the other it is incorporated into medicine, pharmacology, ecology, and agriculture.

One of the main goals of this book is to show the unlimited possibilities of physics in the knowledge of life. However, these possibilities cannot be realized independently of biology (and chemistry). In our time, at a period of integration of the sciences, one must be not only a physicist, biologist, or chemist, but also a natural scientist in the broad sense of the word. The sciences unite. To study life, it is necessary to know zoology and botany, cytology and physiology.

Genuine biophysics is a rather young science. We often meet with problems whose physical solutions are as yet impossible because of the insufficiency of our biological knowledge. Therefore we should not be surprised by the appearance of speculative and pseudoscientific ideas that pretend to be related to biophysics. Some of these ideas are considered in the last section of the book. Notwithstanding its youth, biophysics can distinguish between truth and its simulation.

In spite of the popular character of the presentation, the reader will repeatedly meet with mathematical formulas in this book. However, a chemist or biologist who is acquainted with elementary courses in physics and mathematics should have no difficulty in understanding the material.

Of course for a deeper acquaintance with biophysics the reader will need other books. Some of them—both the popular and the rather serious ones—are listed at the end of the book.

Critical remarks will be accepted by the author with gratitude.

Contents

CHAPTER 1

Contemporary Biophysics

In the beginning of the twentieth century, natural science entered an era of accelerated development. The fundamentals of science—the concepts of space and time, matter and field—underwent tremendous changes. The development of science in the twentieth century has been shaped by the revolution in physics, climaxing with the theory of relativity and with quantum mechanics. The revolution in physics in turn transformed the fundamentals of chemistry: the explanation of Mendeleev's periodic law and the theoretical treatment of chemical bonds and reactions. Physics and chemistry, which previously had combined mainly at the phenomenological level (chemical thermodynamics, theory of solutions, chemical kinetics), became united. Great changes also occurred in the *Weltanschauung* of science: hand in hand with the increasing specialization of knowledge came a strong tendency toward integration.

In the second half of the twentieth century, physics, chemistry, and biology were united in the discipline of molecular biology, which uncovered the physical and chemical essence of the fundamental phenomena of life. Simultaneously, entirely new fields of science, such as cybernetics and information theory, sprang up. The relationship between pure and applied science changed. The gap between theories and their practical applications narrowed. Humanity entered a period of scientific–technical revolution affecting all areas of natural and humanitarian sciences, technics, agriculture, and medicine.

In these conditions, which are unprecedented in human history, the question of the relationship between physics and biology takes on great importance. Are the physical principles and laws, discovered mainly in studies of the objects and phenomena of nonliving nature, sufficient to explain the phenomena of life?

Various answers to this question are possible. The first answer is yes, they are sufficient. The second answer is not so definite: they are not sufficient, but the future development of biophysics, the physics of the life phenomena, will lead to the discovery of completely new physical principles and laws that will not contradict the previous ones. This new physics will form the basis of a scientific explanation of the phenomena of life. The third answer is negative: physics is not and never will be able to explain biological phenomena because they follow purely biological laws, which cannot be explained on a physicochemical basis. This answer comes from the doctrine of vitalism, which was widespread in biology of the last century and which still has some adherents nowadays.

Finally, the ideas of Niels Bohr hold a special place in the solution of the question [1].

Bohr formulated the complementarity principle, according to which the examination of the material world meets with complementary characteristics and notions. For example, in quantum mechanics, the physics of the microworld, the microparticle's coordinate and velocity are complementary, that is, each of these quantities can be measured separately with any precision, but they cannot be measured simultaneously; precise measurement of the electron's position makes the determination of its velocity impossible, and vice versa. The nonexactness of coordinate Δx and velocity Δv is related by Heisenberg's uncertainty principle (see [2])

$$\Delta x \, \Delta v \geq \frac{h}{4\pi m} \tag{1}$$

where m is the mass of electron and $h = 6.62 \times 10^{-27}$ erg sec is Planck's constant. When Δx tends to zero, Δv tends to infinity, and vice versa.

Bohr considered biological laws as complementary to the laws governing nonliving bodies. In other words, it is impossible to study simultaneously the atomic–molecular structure of the cell or organism and its behavior as a total biological system. Bohr considered life the main postulate of biology that cannot be analyzed further, in the same way that the existence of the quantum of action is the nonanalyzable basis of atomic physics [1]. Thus, biology on one hand and physics and chemistry on the other appear to be incompatible, though they do not contradict each other.

Later, Bohr changed his point of view. Instead of the complementarity of the physical sciences with biology, he began to speak of complementarity between physicochemical considerations practically applied to biology and notions which were directly connected with the integrity of organism. Reality is determined not by the postulative character of the notion of life, but by the extreme complexity of the living organism. Not long before his death, Bohr spoke only about practical (and hence surmountable) complementarity of biology and physics [3]. (See also Bohr's letter to the author published in [4].)

Let us return to the starting point. For a serious analysis of the problem it is necessary to determine what physics is.

Physics is the science that studies the structure and properties of concrete types of matter (i.e., substances and fields) and the forms of their existence, of space, and of time. Although this definition is very general, the whole development of physics agrees with it. The main problems of modern physics are in cosmology, the study of the universe—past, present, and future—as a whole, and in elementary particle physics, the study of the microcosmos. These disciplines come together.

Two other fundamental natural sciences are chemistry and biology. Chemistry is the science of the transformations of electronic shells in atoms and molecules during chemical reactions; biology is the science of life phenomena. We see that the definitions of physics, chemistry, and biology are incompatible in the sense that the separation of natural science into these three disciplines is not absolute; the definition of each does not exclude the others. Of course, we have called three great sciences that exist in reality and are intensively developed.

From the general definition of physics, one might think that all other natural sciences, especially chemistry and biology, can be reduced to it. All natural sciences study matter. Do we return to the understanding of physics in its prescientific period, as expressed by Aristotle? Are physics and natural science identical notions?

No, chemistry and biology are characterized by independent methods of research and by laws discovered with their help. In this context the word "reduce" is meaningless. The ideas suggested mean only that physics forms the theoretical basis of all fields of natural science. The establishment of this theoretical basis means the deepening of every science, the investigation of the fundamental laws that explain the phenomena it examines. In chemistry this basis has been already established. In biology, which studies much more complicated phenomena, it has not; but proceeding from the given definition of physics, we must conclude that physics will be the basis of the theoretical biology of the future.

However, this statement is completely insufficient, for it is based only on general reasoning. For the consideration of the relationship of physics and biology, it is necessary to investigate the following: What does physics give to biology now? How does physics answer the questions about the essence of life phenomena? How did biophysics develop? Does biophysics meet with principal difficulties and limitations? As will be shown further, there is reason to suggest that modern physics is sufficient for the understanding of biological phenomena. Stated differently, there is no limit to the application of existing physics to biology. Hence there is no reason to think that biology will require the creation of a new physics.

There have indeed been situations in science that have required the creation of a new physics. The theory of relativity was constructed because classic electrodynamics could not explain the contradictions that appeared in the examination of electromagnetic fields of moving bodies; the famous 1905 paper in which Einstein first formulated the special theory of relativity had the title *Zur Elektrodynamik bewegter Körper*. In a similar way, quantum mechanics was created to overcome the deadlock into which classical physics had fallen while examining the radiation of solid bodies. In both cases, the new theories did not reject the old ones, but included them as a special case.

To solve the problem of the relationship of physics and biology, we must investigate the place occupied by cells and organisms in the enormous hierarchy beginning with elementary particles and ending with the galaxies and the universe as a whole. It is important to identify the main phenomena of life, and their differences from and similarities with the phenomena of nonliving nature. Thanks to the development of biology, today it is not only possible to ask these questions, but to answer them as well, though only partly.

Cells and organisms are macroscopic systems composed of multitudes of atoms and molecules. The smallest cell—the bacterium *Mycoplasma laidlavii*—has a volume 10^9 times greater than that of an atom. Therefore, the biological physics of cells and organisms cannot be directly relationed to the physics of the microworld. The relevance of quantum mechanics to biology is in examining the structure and properties of atoms and molecules that execute biological functions.

Living systems are characterized by two main pecularities. First, they are open systems that exchange matter and energy with the surrounding world. Second, they are historical; each cell and each organism develops and changes in time, and its present state is the result of its individual development and of general evolutionary development.

At this point it is necessary to define life. One of the first scientific definitions, based on the achievements of chemistry and biology of the last century, was suggested by Engels: "Life is the form of existence of the proteinic bodies, the essential feature of which is the constant exchange of substances with the surrounding environment." [5] Two concepts are emphasized in this definition. The first is the determinative role of proteins in life phenomena. This concept has been confirmed by the whole further development of science. As we now know, the proteins are responsible for all processes that take place in a living organism, although other substances are also important for life (especially the nucleic acids, which organize the synthesis of proteins in cells). The second concept contained in the definition of life given by Engels is metabolism, the exchange of substances, which makes the living system an open one.

Let us suggest an expanded definition of a living system based on current knowledge in biology, biochemistry, and biophysics.

The living organism is an open, self-regulated, and self-reproducible system that is far from equilibrium, that develops in an irreversible way and that arises as a result of individual and evolutionary development; it is a heterogeneous system consisting of multifarious big and small molecules. The most important substances in the organism are the biopolymers, big molecules of proteins and nucleic acids.

The heterogeneity of a living organism must be emphasized. There is no such thing as a "living molecule." Despite its complexity, a single molecule of the protein or of the nucleic acid does not live, and in this sense is like the molecule of sugar or CO_2. Obviously, the creation and existence of the systems that correspond to the given definition of life are connected with many problems of physics. If physics must explain the phenomena of life, it must

(i) discover the main laws of behavior of the open nonequilibrium systems, that is, discover a thermodynamic basis of life;

(ii) interpret theoretically the phenomena of evolutionary and individual development;

(iii) explain the phenomena of self-regulation and self-reproduction;

(iv) uncover the nature of biological processes at the atomic–molecular level, that is, discover the connection between the structure and biological function of proteins, nucleic acids, and other substances that act in cells; and research the physical phenomena in living systems at higher overmolecular levels, at the level of cells and organoids forming them;

(v) devise (and provide theoretical explanations for) physical and physicochemical methods of investigation of the biologically functional substances and overmolecular structures built by them; and

(vi) give a physical explanation of a vast complex of physiological phenomena, such as generation and propagation of nerve impulses, muscle contraction, reception of external signals by the sensory organs, and photosynthesis.

Substantial success has been achieved in these six areas. At the same time, science is far from a genuine understanding of the phenomena of life because of the extreme complexity of living systems and the insufficiency of biological, biochemical, and biophysical knowledge. Rigorous formulation of the physical problem, that is, formulation on the basis of general physical laws and atomic–molecular presentation, is now possible in biology only in a limited number of cases. The set of essential biological problems is very far from physics and chemistry. We know almost nothing about the material nature of higher nervous activity, be it memory and thought in higher vertebrates or complicated instinctive behavior in insects.

The items listed above are the subject of biophysics. This science is now changing from an auxiliary part of biology into the very physics of life phenomena. Not all biologists agree with this statement; many of them think that the aim of biophysics is to apply physical methods to biology. This is obviously wrong: From the beginning, biology has used the microscope, a complicated physical device. A much more simple but surely also a physical instrument is the medical thermometer. It makes no sense to say that the application of microscope, thermometer, or even electrocardiograph is biophysics, although one humorous definition of biophysics says that it is the work of a medical doctor who is using a device too complicated for his understanding.

Of course, what branch of science the methods come from is not really important. Biophysical investigations begin with the physical formulation of a problem relating to life phenomena. This problem can be solved by other methods, for example, biological or chemical ones, as long as they are valid scientific procedures.

The interaction of physics and biology is old enough. Descartes sought the explanation of the blood circulation in mechanics, considering the human body as a kind of machine. Similar ideas were developed in Borelli's two-volume treatise *About the motion of animals* (1680–1681). The concepts of mechanics in the epoch were very naive, but for those times they were progressive, for they were an attempt at scientific interpretation of life phenomena. The discovery and research of electrical phenomena in the eighteenth century introduced the idea of "animal electricity" as the main regulator of life. Galvani discovered electric stimulation of muscular contraction and came to the important conclusion that animal and machine electricity are identical. Those and other discoveries developed the understanding of the unity of physical processes in living and nonliving bodies. Lomonosov wrote that "Physiologists must give the causes of the motion of a living body from physics."

In 1780, Lavoisier established the unity of burning and respiration, and in 1828 Wöhler synthesized a substance of living origin—urea—from inorganic substances. The chemistry of life began to unite with general chemistry.

In the nineteenth century, the foundation of scientific biology was laid: Darwin proposed the theory of evolution and Mendel discovered the fundamental laws of genetics. The investigation of biological phenomena had a powerful impact on physics. The law of conservation of energy was discovered by Mayer and Helmholtz, who investigated physiological and medical problems. In 1841, Mayer directed his attention to the fact that the color of the venous blood of people living in the tropics is as bright as that of the arterial blood. He concluded that when the temperature of the environment rises, less energy is necessary for the maintenance of constant body temperature, and he came to formulate the general law of energy conservation and to estimate the mechanical equivalent of heat. Helmholtz considered vitalism, according to which life phenomena are determined by some *vis vitalis* that is inaccessible for scientific cognition, as attributing the features of *perpetuum mobile* to the organism. He formulated the problem of constructing a physics based on the impossibility of existence of perpetual motion, and solved this problem by formulating the law of conservation of energy

(1847). At the end of the nineteenth century, the validity of the law of conservation of energy expressed as the first law of thermodynamics was confirmed for living organisms by direct quantitative experiments. We may say with some exaggeration that if physics gave biology the microscope, biology gave physics the law of conservation of energy.

Boltzmann, founder of statistical mechanics, called the nineteenth century the century of Darwin and studied the mechanical basis of evolution of a physical system. This evolution is described by the second law of thermodynamics, according to which an isolated physical system evolves toward the equilibrium state characterized by the maximal disorder (entropy).

In the second half of the nineteenth century and in the beginning of the twentieth, a set of physical investigations of physiological processes was performed. In particular, Helmholtz studied vision, hearing, and muscular contraction on a physical basis; he was the first to measure the velocity of propagation of the nervous impulse. In 1902, Bernstein discovered biopotentials and established the ionic nature of nervous excitation. One of the first to give a molecular–physical interpretation of heredity was Koltsov (1928) [6], who suggested the first molecular model of the gene. Bauer was the first to suggest a thermodynamic interpretation of life: life is a set of processes that take place in an open nonequilibrium system [7]. Later on, the thermodynamics of biological phenomena was developed in the works of Bertalanffy, Onsager, Prigogine, and others. In 1930, Volterra carried out a mathematical analysis of the so-called "predator–prey" model of the interaction of animal populations [8]. This work is the basis of contemporary physicomathematical modeling of biological processes. We shall speak about biological thermodynamics and mathematical models in the last chapters of this book.

In 1935, Delbrück, Tymofeev-Resovski, and Zimmer discovered the physical nature of mutations. In 1945, Schrödinger, one of the creators of quantum mechanics, published his classic *What is Life? The Physical Aspect of the Living Cell* [9], a book which played a great role in the development of molecular biology and biophysics. Unlike Bohr, Schrödinger suggested the possibility of a general physical interpretation of life phenomena. He formulated a few fundamental physical questions and gave clear answers to some of them. The other questions were answered by molecular biology later on.

The first important question discussed by Schrödinger was How is the nonequilibrium state of the organism maintained? The answer he gave is that the state is maintained by an outflow of entropy from the organism to the surrounding medium.

The second question is Why are atoms small? First, however, we must ask, What does it mean that they are small? In comparison with what are they small? The answer is that atoms are small in comparison with the dimensions of the body of the man; man and the smallest cell consist of a very great number of atoms. Therefore the question may be formulated differently: Why must the organism consist of a great number of atoms? Schrödinger answers: It is because a system consisting of the small number of atoms cannot be ordered; its order would be violated by the accidental fluctuations of thermal motion.

The third question is How can we explain the high stability of the gene, the molecules of hereditary substance built by the light atoms C, H, N, O, P? The hereditary characteristics and the constancy of the biological species are preserved for a great number of generations. Molecular biology, with the help of physics, answered this question, for it discovered the molecular structure and properties of genes, that is, the molecules of deoxyribonucleic acid (DNA).

This extremely short description of the history of biophysics brings us to its modern state, to which this book is devoted.

Nowadays biological physics is developing on a wide front. It is usually divided in three parts:

(1) molecular biophysics, which studies the structure and properties of biologically functional substances and the complexes built by them;

(2) biophysics of the cell, which studies overmolecular, cellular, and subcellular systems; and

(3) biophysics of complicated systems, which deals mainly with physicomathematical modeling of biological processes in cells in the physiological systems of the organisms, in the organisms, in the populations, and in the biosphere as a whole.

The most general problems of biological thermodynamics, information theory, and the physical theory of biological development are connected with the biophysics of complicated systems.

This book follows the above sequence. We begin with molecular biophysics and end with a discussion of general questions.