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The Thermodynamic Theory of Evolution and Aging

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Abstract—Life in the Universe emerges and develops under certain conditions in accordance with the general laws of nature, in particular, in accordance with the law of temporal hierarchies, the second law of thermodynamics, and the principle of substance stability. Biological evolution and an organism's aging are accompanied by changes in the chemical and supramolecular compositions of living bodies. As demonstrated by the author in 1977, these well-known changes have a thermodynamic origin. The phenomenological hierarchical thermodynamics of near-equilibrium quasi-closed systems allows us to explain and predict evolutionary transformations in the living world. From the viewpoint of the rich-energy substance of biological objects, the phenomenon of life, first and foremost, is the struggle for rich-energy chemicals. The accumulation of these substances in biological systems is associated with the directing of the specific Gibbs function of formation of supramolecular structures of living organisms to a minimum. Development of classical science opens up new horizons to explore the real world and contributes to the success of gerontology and geriatrics. This paper is a brief review containing new results.

Keywords: biology, gerontology, principle of substance stability, aging, thermodynamics, evolution

DOI: 10.1134/S2079057014020064

“One of the principal objects of theoretical research in any field of knowledge is to find the point of view from which the subject appears in its greatest simplicity.”
J. Willard Gibbs (1881)

THERMODYNAMICS

Thermodynamics controls everything that happens in the world. Thermodynamics in its classical meaning is based on general laws of nature and relies on a set of total differentials [1, 2, 4–6]. It is possible to apply thermodynamics to the study of idealized equilibrium systems, as well as the study of real quasi-isolated or quasi-closed systems and quasi processes. In addition, it can be applied for the study of processes that occur in complex open systems. In other words, thermodynamics can be used as long as it is possible to assume that the state functions of systems (i.e., functions with total differentials) have a real sufficiently accurate physical meaning. The study of quasi-isolated or quasi-closed systems and quasi-equilibrium processes is enabled by the use of kinetic (linear) thermodynamics methods, assuming that the functions of state of these systems are close to the functions of state of equilibrium systems with a given approximation. *The concept of total differentials is a mathematical foundation, which allows one to univocally characterize the physical state of an equilibrium or quasi-equilibrium thermodynamic system or its subsystem.* Modern thermodynamics pays special attention to both spontaneous and unspontaneous processes that occur under the influence of any physical forces and effects that impact homogeneous or heterogeneous systems [1, 4–6, 8].

The systems and processes that do not belong to the above-described cases are not considered by thermodynamics in the strict sense of the term. They can be studied by pure kinetic methods. However, it should be noted that many authors have considered and still consider that some sections of knowledge that are relevant to the field of kinetics are related to thermodynamics. These areas of knowledge are, for example, the “thermodynamics” of systems and processes that are far from equilibrium, as well as “thermodynamics” of dissipative structures introduced by Ilya Prigogine. Mathematics-based thermodynamics can explore similar (uniform) systems usually relating to a monohierarchical type. This is the only case where it is appropriate to write any prescriptive differential equations whose solutions have a real physical meaning. Thermodynamics can also help to examine interactions between structures that belong to different hierarchies. However, in this case, one can observe the emergence of nonlinearities that hinder the scientific interpretation of research results.

Because biological systems are polyhierarchical, their general description (simultaneously considering all process details at all hierarchical levels) is not useful from a scientific point of view. However, if it is possible to identify individual temporal hierarchical levels in biological systems, transformations at such individual

hierarchical levels can be studied independently. This also allows one to investigate the interaction of adjacent hierarchical levels in the linear approximation and also to apply the principle of substance stability [4, 8, 9, 13].

The law of temporal hierarchies allows one to apply thermodynamics to living systems, as well as many real-world systems, such as a number of geological, atmospheric, and environmental systems [4, 8, 10, 13]. This law paves the way for a sound application of thermodynamics to the evolution of the universe and answers the following question: “Why can thermodynamics be applied to any living and non-living system marked by multi-scale (independent) temporal processes?”

FOUNDATIONS OF THE THERMODYNAMIC THEORY OF EVOLUTION AND AGING OF LIVING CREATURES

This section presents basic principles that are applied by the author in order to develop a hierarchical thermodynamic theory and to prepare new papers, including those included in Knol in 2008–2011 [2, 4, 7, 8]. The main purpose of the recent research studies is to clarify and examine the thermodynamic theory of the origin of life, biological evolution, and the aging of living organisms. In addition, some theoretical principles are extended to other stages of the conscious evolution of all matter.

For many years, the author has been improving this theory, which has been exposed to gradual evolutionary transformations. However, the initial theoretical foundations have remained unchanged. The results were obtained based on the development of classical (equilibrium) thermodynamics applied, with reasonable approximation (quasi-approximation), to dynamic evolving systems that are open for a long period of time. The successful use of quasi-approximation for the thermodynamic description of biological evolution, as well as phylogeny and ontogeny, was made possible thanks to the fact that our life (as a phenomenon) is only possible within a relatively narrow range of fluctuating physical parameters.

In the process of developing the theory, the author did not use any interpretation of “thermodynamics” that was far from equilibrium systems, or many other eclectic provisions of “non-classical science.”

If one assumes that science is designed to create and systematize objective knowledge about reality, one should recognize the fact that, above all, in science “language should be that of mathematics.”

Science is based on models that are only accurate by definition. The world forms diverse structural and temporal hierarchies whose interactions are associated with different forces; these interactions are characterized by energies of a different scale. Therefore, mathematics is of no use for any attempt to create general integral descriptions of the world (systems formed by

various heterostructural heterogeneous objects). *To identify common natural phenomena on the physical basis, mathematics, the language of science, requires simplicity and similarity (sameness or uniformity of the studied objects, processes, and phenomena)* [16].

It is interesting to note that the rise of the modern thermodynamic theory of biological evolution is primarily due to the realization of the fact that the change in the chemical composition of living organisms and their parts in the process of ontogeny and phylogeny (evolution), which is well-known since the early days of modern chemistry and biology, has a thermodynamic origin. This was highlighted by the author in 1976–1977. At that time he analyzed the patterns of evolutionary changes in the chemical (molecular) and supramolecular compositions of organisms and their tissues in the process of ontogeny (aging), phylogeny, and evolution [4, 7, 8]. The identified regularities formed the basis for the formulation of the thermodynamic *principle of substance stability*, which is common to all hierarchies of living matter. This principle allowed one to understand the fact that from the viewpoint of the energy intensity of living objects, life represents a struggle for rich-energy chemical matter [4, 7, 8]. Rich-energy chemical matter is accumulated in biological objects, primarily due to the tendency of the specific Gibbs function of formation of an organism’s supramolecular structures to reach a minimum. These conclusions were possible due to the formulation of the law of temporal hierarchies, as well as the introduction of the concepts of quasi-closed quasi-equilibrium systems (subsystems), which can be distinguished within large-scale open real-world systems.

While publishing some notes and papers, the author has always been guided by the idea that *evolutionary changes in the explored system of any hierarchy are primarily associated with the impact produced by the influx of different types of energy and matter, which primarily originate from the environment surrounding an isolated quasi-closed system. Quasi-equilibrium thermodynamics, guided by the principle of substance stability, shares (distributes) the synthesized and disintegrated matter of the system between different hierarchical structures and stimulates metabolism by using chromatographic and other dividing mechanisms. The evolution of living (as well as non-living) objects proceeds with the participation of unspontaneous and spontaneous processes. Structural hierarchies continuously undergo some changes under the influence of a new substance, physical fields, and other external factors. Under the influence of thermodynamics (phenomenological thermodynamics of close to equilibrium systems), hierarchies mutually adapt to each other. Thus, for example, new species and ecological systems emerge and living objects evolve* [2, 4, 9]. For example, the emergence of new species can be vividly illustrated by the fact that various species of fish live at different levels of depth in the Congo River.

From the perspective of spontaneous transformations, one can introduce the following definition of life: *life as a spontaneous phenomenon is an aggregate of interconnected hierarchical processes related to the circulation of matter in the biosystems of the Earth or other celestial bodies, i.e., the processes that tend to dissipate the Gibbs free energy to the maximum extent.* One should note that there are other definitions of life, which highlight various specific features of life [2].

In the presence of metabolism, the structures of DNA, proteins, and other molecular components adapt to the surrounding molecular environment due to metabolic feedback. One should also mention the ability of organelles to adapt to the cellular medium, cells to the tissue of an organism, organs to the organism media, and organisms to their habitat, etc. In these cases, various hierarchies of matter flows, as well as various physical fields and forces, influence the corresponding structure. Each hierarchy structure, similar to sea pebble particles, are somehow gradually “washed” by the changing environment and subjected to the actions of fields, forces, and influences that can influence the structural transformation of these hierarchies. All these transformations are described in the framework of a general “symbolic” equation of the hierarchical thermodynamics of complex systems [2, 4, 8].

The issues described in this section form the basis of the thermodynamic theory of evolution of the real world. The development and application of these provisions is explicitly or somehow invisibly reflected in the presentation of different sections of the theory. The theory, as well as other scientific research studies, allows one to gradually convert many sections of life sciences from “science in pictures” into a physically grounded knowledge.

The author is not aware of any biological phenomena that, at least basically, cannot be understood from the perspective of the thermodynamic theory. The author believes this theory can stimulate the development of many areas of knowledge in biology, medicine, and other sciences.

To conclude this section, some basic generality needs to be formulated.

The existing observations and experimental data suggest the following: methods of equilibrium (quasi-equilibrium) thermodynamics of complex systems with a good approximation can be used for the description of several stages in the evolution of matter, in particular the stages of nucleation and evolution of life. Physics-based phenomenological hierarchical thermodynamics of natural systems that are close to equilibrium allows one to understand many evolutionary changes in the world in-depth.

More details about previous studies in the field of evolutionary thermodynamics that were accomplished by the author in 1977–2009 are contained in the entries of the EoHT encyclopedia (<http://www.eoht.info/>). However, it should be noted that based on the classical foundation the author’s works are often not

consistent with the ideas of other authors, who tend to rely on physically ungrounded models [2]. For example, the above noted work clearly refers to the non-scientific “generalizing concepts of molecules,” whereas the existence of life as a phenomenon is completely denied. As well, the editor of the encyclopedia sometimes corrects other authors’ theories based on his own personal view, which sometimes causes great confusion. The above-mentioned encyclopedia contains articles that not only reflect various developmental stages of official science, but also “theories” and other ideas expressed by non-professional scientists and amateurs.

LIFE IS NO LONGER A MYSTERY

Various definitions of the phenomenon of life can be found. Yet, it appears impossible to give one single definition. This is primarily due to the fact that life is a complex polyhierarchical homogeneous–heterogeneous process or phenomenon that cannot be represented by unified non-symbolic mathematical equations because mathematics favors the homogeneity and simplicity of investigated objects. This implies that life can only be defined from various perspectives [2].

Is there anything that would generally characterize life as a phenomenon? One of the common general concepts of life is undoubtedly associated with the hierarchical structure of living objects and the “hierarchical mechanism” of the rise and development of life [2, 4, 8]. The commonality that is characteristic of life is due to the laws of thermodynamics and seeks to minimize the specific “free energy of formation” for all elements of hierarchical structures. A living system is a thermodynamically renewing set of hierarchical quasi-equilibrium structures isolated (allotted) in space.

Life on Earth is only possible if there is liquid water in the environment in which one can observe transformations of labile chemical compounds and supramolecular structures that change their composition and conformational structure. Given the fact that water exists in a liquid state under very restricted conditions, the range of conditions for life is relatively narrow. This range limits the temperature interval for the manifestation of life to the conditions of the existence of liquid water and its physiological solutions. A variety of chemical molecules that formed through the interaction of some chemical elements gives rise to a variety of phases and complex heterogenic formations–hierarchical structures. *The existence of organic molecules, which primarily contain hydrogen, carbon, nitrogen, oxygen, sulfur, and phosphorus, in a relatively narrow temperature range suggests that the indicated elements can be considered as the same type from the viewpoint of the hierarchical thermodynamics of living systems.*

Under the Earth’s conditions, thermodynamically stable substances, primarily water, carbon dioxide, nitrogen, phosphorus, sulfur, and other sulfur con-

taining minerals, provide the basis for the appearance and development of life. Many of these substances, when exposed to light, electrical discharges, heat, and other factors, are transformed into thermodynamically relatively *unstable* products that are subject to spontaneous chemical reactions. The products of such reactions gradually spontaneously transform in relatively stable supramolecular structures and increasingly complex and relatively stable structures of higher hierarchies. All hierarchical structures renew "at appropriate times." At the same time, they disintegrate into most rich-energy and chemically labile substances. However, due to the effect of supramolecular thermodynamics (in particular, the principle of substance stability), they are constantly replaced with new similar compounds. Life ends after the cessation of renewal (self-renewal) of the vital parts of biosystems (cells, organisms, populations, ecosystems, and others). Next, a dead body (any biological system) is subject to decomposition or rotting and transforms into the original thermodynamically stable products (water, carbon dioxide, and others). This is the end of the dynamic "vital component" of the matter and energy exchange cycle, which is characteristic of biological matter. It should be noted that the transitions of nonliving substances into more stable products in open natural systems occur in one or several stages without giving rise to thermodynamically generated isolated hierarchical structures. In other words, in this case, polyhierarchical structures that could be regarded as individual relatively stable objects do not emerge.

Thus, life is a hierarchical multistage process that occurs in an aqueous medium under relatively constant conditions in the world. The formation of minerals and sedimentary rocks is a process that occurs in a variety of conditions without the formation of hierarchically allocated intermediates. One should note that the introduced definition of life is different from the above definition because it is formulated from another perspective.

From the viewpoint of evolutionary forces, one can provide another relatively broad definition of life: "Life is a phenomenon of the existing isolated renewing polyhierarchical structures that form with the participation of physical forces and fields in the process of circulation of labile chemical matter in the presence of liquid water on the planet" [2].

From the perspective of living objects as systems, *life on Earth can be regarded as a form of relatively stable existing multicomponent system in a hierarchical world on a planet.*

Life seeks the specific minimum of "free energy" of formation of dynamic hierarchical structures based on the principle according to which "like interacts with the structurally similar, which tends to unite or transform." The involvement of different atoms (chemical elements) located in close proximity to each other in molecules and local supramolecular areas of biological

structures creates a huge variety of structures of different hierarchies in the presence of water. Thermodynamics "identifies" structural fragments of different hierarchies and "contributes" to their interaction with contracting and interacting structures. This occurs at all levels: molecular, supramolecular, organismal, population, and others. Thus, various structures (conformations) of molecules, macromolecules, and supramolecular structures emerge in an aqueous medium with hydrogen bonds and, in a similar manner, various forms and structures of organisms, families, classes, populations, ecological systems, and other living entities.

Such principles of organization of living matter remind one of well-known chemical rules, for example, "like dissolve like," "acid tends to react with base," and "mutual affinity unites molecules." In many social hierarchies there are numerous examples of insects, animals, and people united in groups, clans, and social structures for a more successful functioning and survival.

The question about the purpose of life is interesting. *From the viewpoint of hierarchical thermodynamics, life tends to the minimum value of the specific Gibbs function (free energy) of formation of all hierarchical structures that are attributed to this function (inherent property of life).* From the above perspective, it is the goal of life as a volatile phenomenon observed in a relatively narrow range of physical and physical chemical parameters and under a certain chemical composition of matter in the areas of its (life) existence.

To conclude this section, one should note that the existence of different definitions of life should not be surprising to researchers. As already mentioned, life is a complex multifaceted phenomenon, which is interpreted differently from the perspectives of various fields of science and different models. In this context, one can recall the words of Mendeleev about the impossibility of characterizing natural objects and phenomena by "one gust of thought." One should always consider the relativity of a given definition, which can be formulated from a variety of viewpoints. This reminds us that everything in the world is relative. In relation to one point of reference, criteria, or approximation, phenomena can be considered simple or complex, steady or unsteady, equilibrium or non-equilibrium, etc.

THE THERMODYNAMICS OF OPEN SYSTEMS

Some authors believe that equilibrium thermodynamics does not apply to open systems. However, this statement is true, as a rule, for homogeneous monohierarchical systems, i.e., the systems that contain the same type of objects. For example, homogeneous chemical systems can be considered as such open systems. This view is generally untrue for heterogeneous systems, in the different parts (subsystems) of which, processes occur on different time scales [2]. The primitive mechanistic view of life, which currently rules

among many researchers, does not help one realize the fact that life is associated with the emergence and development of hierarchical structures. The appearance of these structures is “due” to a general law of nature, i.e., the law of temporal hierarchies and the second law of thermodynamics. A significant distinction between the lifetimes of the structures of different hierarchies (relaxation times) allows one to use the methods of equilibrium (quasi-equilibrium) thermodynamics in order to investigate the origins and evolution of living matter. An outstandingly paradoxical situation has emerged. On the one hand, physicists are well aware of the fact that “physics is based on the division of time.” On the other hand, some researchers who study the phenomenon of life are reluctant to apply this provision to living objects. Yet, nature ensures time division, which manifests itself in biology through the law of temporal hierarchies.

The abundant evidence of the applicability of equilibrium thermodynamics to the processes that occur in open natural systems is well known to geologists and other researchers in the field of earth science. Equilibrium (quasi-equilibrium) thermodynamics is used in thermodynamic calculations of chemical processes in stationary reactors, chromatographic columns, and other open systems. A good example that illustrates the applicability of methods of classical thermodynamics to open systems is represented by the processes of rusting in water pipes and in natural conditions [2]. The processes of iron oxidation in the presence of water can be investigated well by applying the methods of equilibrium thermodynamics. These processes are discussed in more detail in the next section.

LIVING SYSTEM MODELS

The wick of a burning candle can be regarded as a quasi-closed quasi-equilibrium dynamic non-stationary system, whose composition changes slowly. The evolution of the composition and structure of the wick as a system is similar to the evolution of the composition and structure of a living organism. The specific Gibbs function of the formation of the supramolecular structure of a burning candle wick tends to a minimum. Rust formation due to iron oxidation is also similar to the aging of an organism from a thermodynamic point of view [2].

The exploration of the evolutionary development of an organism from the viewpoint of hierarchical thermodynamics of close to equilibrium dynamic systems (structures) involves the study of transient aging of cells, vessels, tissues, organisms, populations, and systems of other hierarchies as quasi-closed systems, that is, the investigation of the evolution of the structure and composition of biological objects. Such a presentation of the problem allows one to apply the aging model of a sorbent (stationary phase) equilibrium (quasi-equilibrium) chromatographic column for the study of evolutionary changes in a living system. Obvi-

ously, the analog of such a model is a candle wick (evolving system), in which the processes of stationary (quasi-stationary) burning occur, but whose structure and composition (wick) changes in the transient regime. In other words, the composition and structure of the wick evolve in the same way as living systems.

In the process of evolution, the wick is enriched with the most stable (from the viewpoint of supramolecular structure) non-volatile combustion products. Over time, the wick material becomes brittle, and the wick can spontaneously remove itself from the combustion zone by breaking. The place of the burnt wick fragment is taken by a fresh part, so the combustion process and the wick’s “aging” generally continues. It can be seen that the evolution of the burning candle wick that periodically is renewed in the combustion zone can be compared with the ontogeny and phylogeny of living organisms as quasi-closed thermodynamic quasi-equilibrium systems.

As already noted, the aging of inorganic substances in a way similar to living organisms can be vividly illustrated by the formation of rust on the iron surface. Here one can observe a simple analogy with a burning candle wick.

Rust is formed as a result of the reaction of iron and oxygen in the presence of water or moisture. Rust is accompanied by a decrease in the Gibbs free energy process. Among the main components of rust are ferric oxide (Fe_2O_3), and a mixed oxide of ferrous and ferric iron (Fe_3O_4). The Gibbs free energy of formation of Fe_2O_3 (solid) under 25°C ($\Delta\bar{G}_f^\circ$) is -177.1 kcal/mol or -1.11 kcal/g. The Gibbs free energy of formation of Fe_3O_4 (hard) under 25°C ($\Delta\bar{G}_f^\circ$) is -242.4 kcal/mol or -1.05 kcal/g. It is clear that the formation of iron oxide at standard temperature is characterized by negative values of free energy and the related processes are, of course, spontaneous [17].

Thus, iron ages in a way similar to living organisms. Blood vessels undergo a similar transformation while aging. Aging of polymeric materials is also accompanied by a decrease in the “Gibbs specific function of formation” of their structure. Certainly, this simple, at a first glance analogy is surprising. However, from the viewpoint of thermodynamics, this analogy is justified.

Unlike the well-known models that co-supply stationary combustion processes (oxidation) in living and nonliving systems, representation models model the evolution of the composition and structure systems. Obviously, the evolution of any system is a non-stationary process. Such physical modeling from the perspective of quasi-equilibrium hierarchical thermodynamics is justified and new.

The models presented confirm the conclusion that the description of the evolution of living organisms (ontogeny and phylogeny) can be made on the basis of hierarchical thermodynamics created on a solid basis of classical science.

THERMODYNAMICS OF THE ORIGIN OF LIFE AND THE PRINCIPLE OF SUBSTANCE STABILITY

General Provisions

In this section, it is shown that the transition of inanimate matter to living matter that occurs under the influence of external sources of energy and thermodynamic forces is determined by the thermodynamic principle of the stability of matter (The hierarchical thermodynamics theory “mandated the origin of life”).

In a brief original formulation the principle of substance stability can be represented in the form of [4, 8, 9, 11, 13]: “During the formation or self-assembly of the most thermodynamically stable structures at the highest hierarchical level (j), e.g., the supramolecular level, nature, in accordance with the second law, spontaneously uses predominantly the least thermodynamically stable structures available from a given local part of the biological system, belonging to a lower level, i.e., molecular level ($j - 1$), and incorporates these unstable structures into next higher level, i.e., the supramolecular level (j).”

Briefly, the principle of substance stability implies that each subsystem in the biosphere evolves according to the thermodynamic trend towards the search for the minimum specific “Gibbs free energy” at each evolutionary cycle. The principle as applicable to the molecular and supramolecular structures was named by the author the principle of the stability of chemical matter. Subsequently, this principle was applied to different hierarchies, i.e., to the evolution of living matter. This principle is also known as the principle of the stability of matter, the principle of substance stability, and the feedback principle.

As already mentioned, supramolecular thermodynamics selects in the process of evolution the *least stable chemical substance* which accumulate in supramolecular abio-genous structures and further in living structures or organisms. These low stable chemical substances spontaneously and relatively quickly decay and are removed from the body. The decayed substances are replenished with new similar compounds, which is typical for metabolism. *The appearance of oxygen in the atmosphere* contributes to thermodynamically favorable degradation of substances through the formation of intermediate oxygen-containing conversion products. All this leads to the emergence of supramolecular subhierarchies and the development of organisms.

In the process of evolution the elemental composition of organisms naturally changes and becomes more sophisticated. To characterize the chemical and supramolecular thermodynamic stability of nucleic acid fragments and their flanking protein and aqueous solutions, it is largely sufficient to consider the presence of the elements C, H, O, N, P, and S in their structures.

The chemical thermodynamic stability of key bonds and nitrogenous nucleobases of DNA and RNA can be evaluated by calculating the specific Gibbs function of formation (specific “free energy” of formation) of these macromolecules (fragments) from simple substances (elements). These estimates are relative and approximate, but have significant physical meaning. This is confirmed by the existing correlations and comparisons of melting and decay temperature ranges of the related substances [2]. Given the known correlations [4, 9], the decomposition temperature of chemical compounds, as well as their boiling and melting temperatures, often serve as a good target for the qualitative assessment of the thermodynamic stability of these compounds and their condensed phases.

The thermodynamic stability of supramolecular structural nucleic acid fragments can be estimated by using the Gibbs–Helmholtz equation and its analog [2, 4, 8], applied to determine the stability of supramolecular structures, which is formed between the inner fragments of chains and external molecules. In this case, the comparison of the melting temperatures of biological structures also serves as a quality indicator of the thermodynamic stability of these structures. The assessment of the thermodynamic stability of supramolecular structures can be performed based on the use of DSC (differential scanning calorimetry). However, in this case the estimate is also approximate. Biological supramolecular structures melt under a relatively wide range of temperatures; therefore, it appears rather difficult to determine the melting point of different fragments of macromolecules and their environment. Yet, evidence that facilitates such an assessment by computing the stability of individual monotype supramolecular structures of biological tissues (e.g., lipids) is known.

A number of assumptions and postulates have been proposed in order to evaluate the thermodynamic stability of supramolecular chemical and biological systems whose chemical and supramolecular compositions vary in the process of evolution. Nevertheless, the known facts and experimental data confirm the relevance of such an assessment. Apparently, this can be explained by the fact that life only exists under a narrow range of temperatures and living systems are composed mainly of elements with close “absolute stability of the same type.” Perhaps, from the thermodynamic point of view, biological systems can be regarded as “quasi-thermodynamic” [2].

Below are the estimates of the thermodynamic stability of individual “primary” simple molecules, chain fragments, and nucleobases of nucleic acids. These estimates are made on the basis of data provided in the fundamental reference work [17]. In addition, a number of articles on this subject can be found on the Internet [2].

Table 1. Primary molecules

Title	Formula	Molecular mass	Melting point, K	Boiling point, K	ΔG_{298}° , kcal/mol	ΔG_{298}° , kcal/g
Cyanogen	C_2N_2	52.036	245.0	252.0	+71.03	+1.365
Hydrogen cyanide	HCN	27.026	259.91	298.85	+28.71	+1.053
Ammonia	NH_3	17.032	195.42	239.73	-3.86	-0.227
Hydrogen sulfide	H_2S	34.082	190.85	212.87	-7.90	-0.231
Methane	CH_4	16.042	90.55	111.42	-12.15	-0.757
Carbon monoxide	CO	28.010	68.15	81.66	-32.81	-1.171
Water	H_2O	18.016	273.15	373.15	-54.64	-3.033

PRIMARY MOLECULES

Let's make a comparison of a number of parameters that characterize the thermodynamic stability of "primary" simple molecules, fragments of macromolecular chains, and some nucleobases of nucleic acids. Next we will show that our estimates of the stability of the main chains and nucleobases are perfectly consistent with the principle of the thermodynamic stability of matter.

Table 1 shows the individual "primary simple" molecules that exist under conditions of the primary (and modern) Earth formed under the influence of external factors (light, electrical discharges, and others), as well as spontaneous transformations. The represented molecules of substances in the state of an ideal gas correspond to chemical "blocks," which are part of the nucleobases.

The data presented in Table 1 allow us to make well-grounded conclusions. The table shows that the molecule C_2N_2 and HCN, as well as others, being unstable (or insufficiently stable) can appear in appreciable quantities, primarily under the influence of external energy sources and participate in chemical reactions to form more stable structures. Water plays a special role in the presented range of primary molecules. Specifically, water plays a pivotal role in the formation of living biological structures. The compounds shown in the table are primarily of interest for chemical evolution. Biological evolution only takes place after the formation of supramolecular structures, which due to thermodynamic factors begin to be renewed and improve [2].

Next, we will discuss the stability of nucleic-acid fragments, whose appearance is associated with the matrix synthesis of these macromolecules formed with the participation of minerals and other matrices that defined the geometric shape of major macromolecular chains, as well as the structural correspondence—complementary of strictly defined nucleobases. It is known that purine and pyrimidine bases are such bases. There is experimental evidence (Golubev et al. [2]) that one of these minerals—matrices is apatite, whose phosphoric acid fragments remain in the main chains of nucleic acids. These fragments and the sugars con-

tained in the chains predetermined "further activities" of hierarchical thermodynamics. Of many alternatives, thermodynamics has only chosen (and still chooses) those which are suitable from the viewpoint of geometrical compliance and minimization, to a certain level, of the Gibbs function of formation of supramolecular structures.

THERMODYNAMIC CHARACTERISTICS OF MOLECULES WHOSE FRAGMENTS FORM KEY NUCLEIC ACIDS CHAINS

Ribose, as well as other L-pentoses, contains five carbon atoms and has a gross formula of $C_5H_{10}O_5$. Deoxyribose ($C_5H_{10}O_4$) also contains five carbon atoms, but only four atoms of oxygen. From the standpoint of chemical thermodynamic stability, these compounds can be considered mono-type.

Ribose and deoxyribose have lower melting points (below $100^{\circ}C$) than most other aldoses (natural sugars). This explains to some extent the fact that these sugars form "optimal" mobile intermolecular bonds with water molecules. Ribose and deoxyribose fragments together with fragments of phosphoric acid (H_3PO_4) form the spiral structure of RNA and DNA. Table 2 shows examples that indicate the relatively high thermodynamic stability of the discussed fragments of nucleic acid chains.

Apparently, crystals of ribose and deoxyribose, together with the structure of apatite and other minerals, served as a common "generic" matrix which participated in the formation of main nucleic acid chains.

It is appropriate to note that thermodynamic values related to biochemical reactions are often treated differently than in the case of ordinary chemical reactions. New approaches to the evaluation of different characteristics of biochemical reactions involving nucleobases, as well as their nucleosides and nucleotides, were developed by Alberti [2]. Problems related to the definition of standard states in thermodynamics were discussed in the paper authored by Vorobyov [2].

Table 2. The building materials of nucleic acid strands

Title	Formula	Molecular mass	Melting point, K	Boiling point, K	ΔG_{298}° , kcal/mol (solid)	ΔG_{298}° , kcal/g
Deoxyribose (D)	C ₅ H ₁₀ O ₄	134.13	364 (91°C)	—	−140	−1.04
Ribose (D)	C ₅ H ₁₀ O ₅	150.13	368 (95°C)	—	−180	−1.20
Xylose	C ₅ H ₁₀ O ₅	150.13	418 (144–145°C)	—	−175.94	−1.172
Phosphoric acid	H ₃ PO ₄	98.00	315.5 (42.35°C)	431 (158°C)	−269	−2.74

Table 3. The thermodynamic characteristics of nucleobases

Title	Formula	Molecular mass	Melting point, K	Boiling point, K	ΔG_{298}° , kcal/mol (solid)	ΔG_{298}° , kcal/g
Adenine (A)	C ₅ H ₅ N ₅	135.13	633–638 (365°C)	—	+71.58 (s)	+0.530
Guanine (G)	C ₅ H ₅ N ₅ O	151.13	633 (360°C)	—	+11.33 (s)	+0.075
Cytosine (C)	C ₄ H ₅ N ₃ O	111.10	593–598 (325°C)	—	Negative	—
Thymine (T)	C ₅ H ₆ N ₂ O ₂	126.11	589–590 (317°C)	—	Ibid	—
Uracil (U)	C ₄ H ₄ N ₂ O ₂	112.09	608 (335°C)	—	"	—

THERMODYNAMIC CHARACTERISTICS OF NUCLEOBASES

Nucleobases are contained in RNA and DNA, and participate in the mating of major chains. Cytosine, guanine, adenine, and thymine are primarily contained in DNA, while in RNA thymine is replaced by uracil. The abbreviation of these bases are C, G, A, T, and U, respectively. The thermodynamic characteristics of nucleobases are shown in Table 3.

The table shows that the purine (A and G) and pyrimidine (C, T, and U) bases have similar high melting points (decomposition). Therefore, they can be considered, from the perspective of thermodynamics, quasi-monotypical. From the viewpoint of thermodynamic chemical stability, the studied compounds are rather volatile. This property is revealed by positive values of the Gibbs function (Gibbs energy) of formation of compounds from elements (simple substances) in the standard state ΔG_{298}° of solid phase (s). According to the principle of substance stability, which has been experimentally proven by the example of hydrocarbons and their derivatives [4, 8], these compounds should form relatively stable supramolecular structures, as observed in practice. In other words, *low molecular (chemical) stability of nucleobases is accompanied by the increased stability of supramolecular structures that are primarily formed by hydrogen bonds*. It is possible to find in the academic literature and on the Internet many publications that contain data on the relatively high stability of supramolecular complementary bonds between DNA and RNA nucleobases in aqueous solutions.

Thus, it is shown on the basis of thermodynamic data that low chemical stability of nucleobases causes relatively high stability of supramolecular bonds between these nucleobases. The relatively high stabil-

ity of the main chains whose structures are formed with the participation of matrix minerals provides intermolecular contacts with the molecules of water. Supramolecular thermodynamics, which seeks to minimize the specific Gibbs function (Gibbs free energy) of formation of structures, selects the maximum complementary correspondence between fragments of macromolecular compounds, water molecules, and other low-molecular-weight substances.

TROPISM AND THERMODYNAMICS

It is reasonable to argue that the well-known phenomenon of tropism has a thermodynamic origin at all structural levels of the living and inanimate world [2, 14, 15]. Tropism at the molecular level plays a crucial role in the transmission of direct and reverse genetic information, as well as the formation and development of new organisms.

The biological phenomenon of a directed growth or rotary motion of an organism, usually a plant, in response to external stimuli is usually called tropism. However, there are other definitions of tropism or tropisms.

A more general concept of tropism is associated with the direction of growth or any directed movement of a living system or its components in response to external stimuli. In addition, under certain reservations, the phenomenon of directed growth and orientation of various hierarchical structures as a result of an external stimulus of an inorganic nature can also be considered tropism. For example, the directional growth of crystals in geological systems or directional movement and transformation of other objects in the non-living world can be attributed to such tropism. The commonality of tropism in all cases is associated with the stimulating effect of the environment. From

this perspective, tropism is a common natural phenomenon.

A broad view of tropism necessitates the distinction between different types of tropism for the purpose of research. Thus, one can refer to tropism as a reaction of the orientation and development of organisms or their communities, as a process of directed growth and movement of cells, organelles, bacteria, viruses, macromolecular fragments, and molecules under the influence of physical fields, light, sound, chemicals, and other factors. However, it is important to bear in mind the fact that many tropisms should, for the sake of clarity, probably be also called behavioral or retaliatory reactions, or be described in other terms [2, 4, 8].

The tropism phenomenon can be relatively easily studied by equilibrium (quasi-equilibrium) thermodynamics. Numerous evidence proving the thermodynamic orientation of tropism is available.

At present, tropism manifested at the molecular level, or, as is often noted, at the nanomolecular level, is of particular interest. For example, such tropism is well-known as the reaction of a variety of chemicals, including medicines and biological receptors. At the molecular level, tropism plays a fundamental role in the origins of life, the transfer of direct and reverse genetic information in the process of evolution, as well as in the processes of initiation and development of a new organism [2–4, 8, 12]. Apparently, the principle of substance stability, as a manifestation of tropism, determines the orientation of phenomena in the interaction of related hierarchies and their constituent structures. In one way or another, hierarchical thermodynamics of supramolecular interactions of complex systems determines the genetic transmission of information, transformation of genes, and the development of living organisms [3, 12]. It is also the driving force behind the origin of life in the Universe.

In previous studies, the author analyzed many transformations that manifest in the living world as the phenomenon of tropism in its extended meaning. However, it should be noted that the author has not always used this term: phenomena were described from the viewpoint of generally accepted (although equivalent to tropism, from a physical perspective) concepts. Thus, the manifestation of tropism was observed in those cases when chemical substances influence the genetic apparatus [4, 10]. The possibility of a softly adapting intervention of chemical compounds in the functioning of genes at a supramolecular level was postulated [4]. Later, similar conclusions were made about the influence of food on the aging of organisms at a molecular level [3, 12]. In this case, consideration was given to the model of an organism viewed as a complex “aging” chromatographic column, where food is digested, and a certain part of the food reacts with hydrochloric acid, being exposed to the activity of enzymes. Next, the “nutritional molecules” (the remaining part of food molecules and undecayed molecules) migrate to various parts of the body in accordance with the thermodynamic stability of supramolecular

structures of the body and the relative chemical affinity of nutrient molecules with their surroundings. Given the correspondence of the introduced model and the data relating to longevity, the gerontological value of food products is determined based on the measurement of enthalpy or heat (more precisely, the Gibbs function) of supramolecular interactions. Thus, the idea that all components of consumed food can be evaluated by the index of gerontological value based on thermodynamic parameters has been additionally substantiated.

In [10] the influence of the guiding action of supramolecular thermodynamics on the genetically determined growth of a developing embryo was considered as a response that is stimulated by its environment. This means that the growth and differentiation of embryonic cells and tissues can be regarded as a manifestation of tropism at a supramolecular level. The manifestation of love and feelings by living organisms can be regarded as tropism in a broad sense of this term. Sociological manifestations of tropism in society [2] are also well known, for example, political decisions entail responses in the form of directed processes in a society.

Such an expanded view of the phenomenon of tropism can be justified from the viewpoint of the theory of the behavior living systems, the principle of Le Chatelier–Braun, and other thermodynamic principles [2, 4].

THERMODYNAMICS OPTIMIZES LIFE

In accordance with the laws of nature, hierarchical thermodynamics creates and optimizes the forms and functions of living systems in the conditions of their habitat [14, 15]. In search of the minima of the specific “Gibbs free energy” (Gibbs function) of structure formation, nature spontaneously reveals the chemical composition and structure of hierarchical dynamic living systems [1, 4, 8]. To study of all of the evolutionary changes in ontogeny, phylogeny, and evolution it is convenient to use the existing (“symbolic”) equation for the total differential of the Gibbs function [2, 4, 8]:

$$dG^* = \sum_i dG_i^* = - \sum_i S_i dT_i + \sum_i V_i dp_i - \sum_i \sum_{k_i} x_{k_i} dX_{k_i} + \sum_i \sum_{k_i} \mu_{k_i} dm_{k_i},$$

where T is temperature; S is entropy; V is volume; p is pressure; X is any generalized force, except for pressure; x is any generalized coordinate, except for volume; μ is the chemical (evolutionary) potential; m is the mass of the k th substance, and the work performed by the system is negative. The i index refers to particular evolution; k to the i th component of evolution. The superscript * means that the behavior of a quasi-equilibrium complex system is considered.

Physical fields and the effects calculated by this equation somehow form or sculpt living objects of chemical substances that are present under the Earth’s

conditions, assigning these objects the corresponding optimal forms and functions [2, 14, 15].

The products of photosynthesis and numerous metabolites formed mainly by covalent bonds are complex biphilic compounds of various types. These compounds show biphilic properties at the nanoscale, as well as at higher levels of living matter in an aqueous medium. They also are united based on the principle that “like tends to like” and form liquid crystal and heterogeneous structures. The biphilic properties of molecules are undoubtedly due to the different nature of atoms involved in their formation. The biphilic (and even polyphilic) property creates diverse supramolecular structures and occurs on a broader scale at the levels of higher hierarchies. As already noted, biological molecules relatively slowly spontaneously transform step by step into stable simple matter. Due to the *principle of the stability of matter* and continuous reproduction, living systems (as intermediate polyhierarchic heterogeneous systems of the noted transformation) exist for relatively long periods. Metabolism in living systems is primarily associated with the optimal difference between chemical and thermodynamic stability of supramolecular structures in their environment. Life manifests itself in the form of intermediate localized polyhierarchic heterogeneous systems (organisms) of these transformations. Life is associated with multiple consecutive homogeneous–heterogeneous transformations.

As already mentioned, one of the essential differences between living and nonliving systems is the inability of inanimate matter to form clearly allocated polyhierarchic supramolecular structures. This conclusion confirms the earlier statement formulated by the author [8]: “The origin and evolution of life is the origin and evolution of thermodynamic self-organized (self-assembled) polyhierarchic systems.”

CONCLUSIONS

Thermodynamics is the driving force of the life, evolution, development, and aging of living organisms. The thermodynamic theory of biological evolution and aging of living organisms is supported by new evidence and contributes to the solution of basic research and applied problems in biology and medicine, including gerontology and geriatrics.

ACKNOWLEDGMENTS

The author is grateful to Professor V.N. Anisimov, G. Arrhenius, S.A. Dzyugan, and V.Kh. Khavinson for their advice and support.

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Translated by V. Kupriyanova-Ashina