PHENOMENON OF LIFE: BETWEEN EQUILIBRIUM AND NON-LINEARITY

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Abstract. A model of ordering applicable to biological evolution is presented. It is shown that a steady state (more precisely approaching to a steady state) system of irreversible processes, under conditions of disproportionation of entropy, produces a lower-entropy product, that is, ordering. The ordering is defined as restricting of degrees of freedom: freedom of motion, interactions etc. The model differs from previous ones in that it relates the ordering to processes running not far from equilibrium, described in the linear field of non-equilibrium thermodynamics. It is shown that a system, which includes adenosine triphosphate (ATP) to adenosine diphosphate (ADP) conversion meets the demands of the physical model: it provides energy maintaining steady state conditions, and hydrolysis of ATP proceeding with *consumption* of water can be tightly conjugated with the most important reactions of synthesis of organic polymers (peptides, nucleotide chains etc.), which proceed with *release* of water. For these and other reasons ATP seems to be a key molecule of prebiotic evolution. It is argued that the elementary chemical reaction proceeding under control of an enzyme is not necessarily far from equilibrium. The experimental evidence supporting this idea, is presented. It is based on isotope data. Carbon isotope distribution in biochemical systems reveals regularity, which is inherent to *steady state* systems of chemical reactions, proceeding *not far from equilibrium*. In living organisms this feature appears at the statistical level, as many completely irreversible and non-linear processes occur in organisms. However not-far-from-equilibrium reactions are inherent to biochemical systems as a matter of principle. They are reconcilable with biochemical behavior. Extant organisms are highly evolved entities which, however, show in their basis the same features, as the simplest chemical systems must have had been involved in the origin of life. Some consequences following from the model, which may be significant for understanding the origin of life and the mechanism of biological evolution, are pointed out.

Keywords: biological evolution, carbon isotopes, disproportionation of entropy, fractionation of isotopes, origin of life, non-equilibrium thermodynamics, ordering

1. Introduction

At present the dominant concept of biological evolution is the Darwinian theory of 'origin of species by means of natural selection'. It offers a mechanism of conversion of casual changes to the directed process of evolution. To that extent, in which the Darwin's concept is applied to phenomena of the adaptation and the biological diversity, it is valid and confirmed by multiple observations. But as a general theory of evolution it faces difficulties. These difficulties stem from the fact

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that Darwin's theory is not a theory of ordering. Natural selection can accompany both the processes of ordering and degradation. However, the most obvious and bright phenomenon of life consists of a high density of ordering and an increase in the ordering in the course of evolution. Therefore, the emergence of life and its evolution on Earth must have been related to the existence in nature of a physical mechanism of ordering. This mechanism should be sufficiently general and at the same time be consistent with the demands of the second law of thermodynamics.

The known models of self-organization adopt the principles of thermodynamics of open systems, natural selection, and involve ideas on hypercycling (Eigen, 1971), initial complexity as a prerequisite of ordering (Dyson, 1980; Kauffman, 1993), and dissipative structures (Glansdorf and Prigogine, 1971). In accordance with a theory developed by Prigogine and his coworkers (Nicolis and Prigogine, 1977; Prigogine, 1980; Babloyantz, 1986; Prigogine and Stengers, 1984), self-organization may occur in irreversible processes, which are far from equilibrium and can be described in terms of non-linear thermodynamics. Moreover, these authors argue that one cannot expect spontaneous ordering in the linear field. This is true for macroscopic spatial or temporal ordering. However, life demonstrates ordering at the microscopic level.

The purpose of this paper is to show that *disproportionation of entropy* in a *steady state* system of *microscopically conjugated* reactions produces ordering. The model is inferred in terms of the thermodynamics of irreversible processes, developed by I. Prigogine. However, while I. Prigogine and his scholars placed the emphasis on non-linear process, that is, far from equilibrium, I argue that ordering under certain conditions is possible in systems which are not far from equilibrium. I also try to show how the physical model can be realized in terms of chemistry. The appropriate chemical model which satisfies the demands of the physical model is ATP hydrolysis conjugated with synthesis of intermolecular bonds (e.g. peptide bonds). This system could have served as an initial chemical machinery producing ordering in the prebiotic world.

The suggested physical model is considered as a model of ordering in general. It pertains to both the prebiotic world and biological evolution. The theorem on minimum entropy production in a steady state, which the physical model employs, is applicable to systems not very far from equilibrium. Is this a property of extant biological systems? The real thermodynamics of biochemical systems is masked by the governing role of enzymes. As isotopic composition is not under enzymatic control (isotopic composition is not encoded; there are no isotope-specific enzymes) the natural distribution of isotopes (especially carbon isotopes) can provide a unique test of the thermodynamic state of biochemical processes. If any proximity to equilibrium is a feature of biological reactions, it should be manifested in a tendency toward equilibrium distribution of isotopes in biomolecules. We shall test this hypothesis.

2. The Physical Model

As is known, any irreversible process is characterized by positive production of entropy: $\frac{\partial S}{\partial t} = \Sigma X_k J_k$, where X_k and J_k are generalized force and generalized flux respectively. Ordering is related to a decrease of entropy that corresponds to the negative sign of the force-flux production. Simultaneous generation of positive and negative entropy (disproportionation of entropy) is possible under two interrelated conditions: (1) the processes (reactions), characterized by positive and negative production of entropy must be microscopically conjugated, and (2) the summary entropy production of both processes must always be greater than or equal to zero, that is:

$$\Sigma X_k J_k \geq 0 . \tag{1}$$

Disproportionation of entropy occurs rather frequently in nature. It manifests itself in different phenomena. For example, in the process of thermo diffusion a substance may diffuse against the concentration gradient. Thus, there is production of negative entropy (consumption of entropy). However, this effect is conjugated with the positive production of entropy due to heat flow, which overcomes consumption of entropy. Under geological conditions, when thermal metamorphism of oil occurs, the hydrocarbons degrade to form simpler low-molecular-weight hydrocarbons, and simultaneously complex bitumen-asphalten polymers form. Disproportionation of entropy occurs on the nuclear level during explosion of supernovae. When enormous pressure crushes atoms, squeezing them to cause conglomeration of neutrons, at the same time synthesis of all heavy nuclei occurs. This extreme process is a source of the chemical elements, which make up the planets and our own bodies. However, separate episodes of ordering do not explain evolution. In order for evolutionary ordering to arise, products from one step of ordering should become a source for the next one. This mechanism can be realized as a consequence of steady state (more precisely approach to steady state) systems of irreversible processes.

In accordance with non-equilibrium thermodynamics, production of entropy in a system (symbol i) and entering the system (symbol e) are balanced in a steady state:

$$-\frac{\partial_e S}{\partial t} = \frac{\partial_i S}{\partial t} . \tag{2}$$

Production of entropy in a steady state is minimal (Nicolis and Prigogine, 1977). Therefore (2) should be presented as:

$$-\frac{\partial_e S}{\partial t} = \left(\frac{\partial_i S}{\partial t}\right)_{\min} . \tag{3}$$

If some additional $X_e J_e$ enters the system (let it be a reaction proceeding with increase of entropy and energy yield), production of entropy in the system should increase:

$$-\frac{\partial_e S}{\partial t} + X_e J_e = \left(\frac{\partial_i S}{\partial t}\right)' . \tag{4}$$

The term on the right with symbol (′) is production of entropy in the newly arisen system. On the strength of the theorem on minimal entropy production in a steady state expression (4) may be presented as:

$$-\frac{\partial_e S}{\partial t} + X_e J_e = \left(\frac{\partial_i S}{\partial t}\right)'_{\min} + X_i J_i . \tag{5}$$

Let us rewrite the last expression in the following way:

$$-\frac{\partial_e S}{\partial t} + X_e J_e = \left(\frac{\partial_i S}{\partial t}\right)'_{\min} - (-X_i J_i) . \tag{6}$$

The minus sign inside the brackets in the last term on the right indicates production of negative entropy and the minus sign in front of this term indicates that the flux moves from the system. In other words, the system yields a lower-entropy product.

It follows from (3) and (5) that:

$$\left(\frac{\partial_i S}{\partial t}\right)_{\min} + X_e J_e = \left(\frac{\partial_i S}{\partial t}\right)'_{\min} + X_i J_i . \tag{7}$$

Hence inequality (1) is satisfied in the form:

$$X_e J_e - X_i J_i \geq 0 \tag{8}$$

since

$$\left(\frac{\partial_i S}{\partial t}\right)'_{\min} \geq \left(\frac{\partial_i S}{\partial t}\right)_{\min} . \tag{9}$$

Thus, disproportionation of entropy in a system of chemically conjugated irreversible reactions creates an act of ordering. Moreover, it follows from (6), that, when

$$\left(\frac{\partial_i S}{\partial t}\right)' \to \min, \text{ then } |(-X_i J_i)| \to \max . \tag{10}$$

Hence, the principle of minimal entropy production in a steady state system is equivalent to the principle of maximal production of the lower-entropy product in microscopically conjugated reactions.

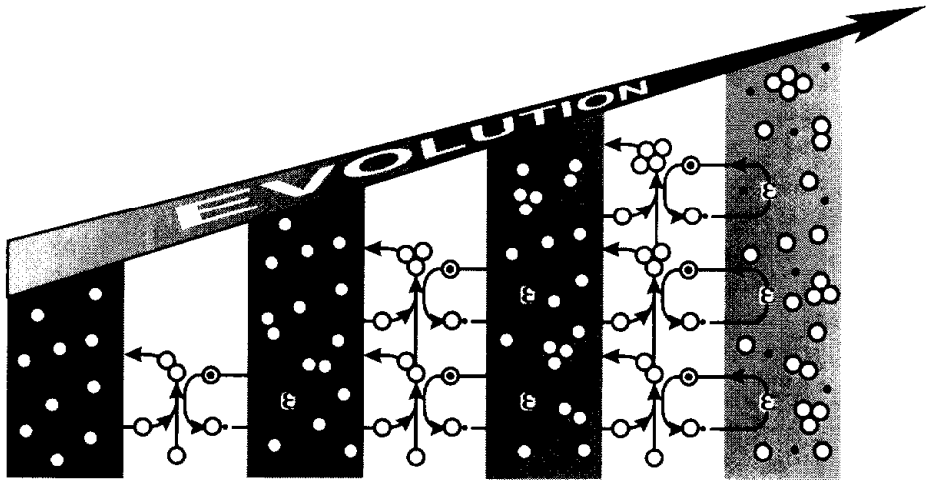

Figure 1. Schematic presentation of the evolutionary ordering in a sequence of interrelated steady state systems.

It is important that this act takes place in a system rushing to a steady state. If the product of the system is involved in a subsequent process, its decrease is compensated by additional production. Thus, as illustrated in Figure 1, an expanding net of interrelated systems, approaching a steady state, may provide evolutionary ordering.

3. The Chemical Model

An example of a reaction system which meets the criteria of the physical model stated above, is the conversion of adenosine triphosphate (ATP) to adenosine diphosphate (ADP), conjugated with formation of organic polymers. Indeed, ATP to ADP conversion provides energy and proceeds with increase of entropy, whereas polymerization of nucleotides, formation of peptides etc., proceed with consumption of energy and decrease of entropy. In addition, polymerization proceeds with the release of water molecules, whereas ATP hydrolysis proceeds with consumption of water. Thus both processes are microscopically conjugated through a common component that is a water molecule.

Synthesis of a polymer from monomers is a process of formation of a lower-entropy product. Indeed, entropy in terms of statistical mechanics is defined by the number of ways W, by which the given system could form: $S = klnW$, where k is the Bolzman constant. Decrease of entropy means restriction of freedom: freedom of motion, interaction, choice etc. Synthesis of a polymer restricts translational and rotational degrees of freedom of every monomer. Chemical ordering means also establishing of functional specialization (chemical selectivity), that is, exercise of

restriction of freedom of interations. It is known that functional specialization in biological systems is realized through biocatalysts (enzymes). Therefore, chemical ordering to a considerable extent is production of catalysts (peptides).

The system of complex enzymes existing in organisms living today is a product of long-time biological evolution. But even short peptides with random sequences of amino acids may be capable of catalytic action. Their emergence might have been an initial step of the chemical ordering in a prebiotic world.

In this connection it is noteworthy that ATP formation might occur in the prebiotic world. Although ATP is a rather complex compound, its organic moieties, adenine and ribose, could form early in prebiotic evolution by condensation of the simplest precursors: hydrogen cyanide (HCN) and formaldehyde (HCHO) respectively. Although some questions concerning ATP synthesis exist (e.g. Shapiro, 1995), scenarios for formation of ATP or similar compounds on early Earth have been suggested (Galimov, 2001, 2002; Baltscheffsky *et al.*, 2002).

The model of ordering stated above suggests microscopic ordering. The process of ordering may be localized at a single molecule. Transformation of the microscopic ordering to a macroscopic level requires a mechanism of self-reproduction. The better term is *iteration*. Iteration, that is, production of self-similar structures, occurs in a wide range of phenomena from molecular autocatalysis to processes of reproduction of organisms, change of generations etc. The microscopic ordering and iteration are two sides of a single process of macroscopic (spatial and temporal) ordering in the present concept.

The question arises how the suggested concept of ordering may be reconciled with the concept of an 'RNA world'. Although we emphasize the role of peptides in the initial evolution, both peptides and polynucleotides might be synthesized in conjugation with conversion of ATP to ADP. Two major properties, which are necessary for evolution, have been divided between two different types of organic structures.

Thus, nature has established a correspondence between polypeptides and polynucleotides by means of the genetic code. We suggest that the RNA and peptide worlds evolved in an interconnected way by means of the ordering-iteration mechanism. These remarks are merely a demonstration of a line of thinking following from the model. It is not my purpose here to discuss the chemical aspects in any detail.

4. Testing Whether Biochemical Processes Are Essentially Linear

Turning back to the physical model, it is important to note that the theorem on minimum entropy production, which we employ, is correct within the field of linear non-equilibrium thermodynamics when the fluxes linearly depend on the forces inducing them. This takes place when the process is not very far from equilibrium.

Is there any evidence that biochemical processes actually run not far from equilibrium? At first thought the highly organized state of biological systems is in obvious conflict with such an idea. However, the main rule of organization of chemical processes in living matter is that all biochemical reactions proceed under the control of enzymes. Enzymes specify chemical reactions: only molecules of specific composition, structure and chirality may interact under control of given enzyme. The system of enzymes inherent to every living entity has been developing for the whole history of the evolution of life.

Therefore, the non-equilibrium appearance of living matter is a result of a specific structure of interactions controlled by a system of enzymes. Instructions about how this system must work are received by each living organism at the moment of its conception via DNA. This instruction has formed over billions years of evolution. The presence of reversibility in enzymatic reactions is therefore difficult to evaluate because of the chemical selectivity of enzymes. *However, enzymes do not control isotope composition of elements.* Isotope compositions is not encoded. There are no isotope-specific enzymes. Therefore, the pattern of natural distribution of isotopes depends only on the type of isotope effects occurring in biochemical processes. If any proximity to equilibrium is a feature of biological reactions, it should be manifested in a tendency toward equilibrium distribution of isotopes.

At equilibrium, the isotope composition of reaction components is related to their respective thermodynamic isotopic factors:

$$\delta_p - \delta_s \cong \left(1 - \frac{\beta_p}{\beta_s}\right) \cdot 10^3‰, \tag{11}$$

where δ_p and δ_s indicate isotope compositions of product (p) and substrate (s) relative to the standard (for instance: $\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard\text{-}PDB} - 1]‰$) and the β-values are the reduced partition function ratios (thermodynamic isotopic factors).

The $\beta^{13}C$-values can be calculated through vibration frequencies when they are known for the isotopic species, or by use of the method of the isotopic bond numbers (Galimov, 1985).

It should be stressed that the thermodynamic isotopic factors describe the distribution of isotopes in a state of isotope-exchange equilibrium. It is known from isotope geochemistry that organic compounds can preserve their carbon isotope composition for many millions of years. Nevertheless, the results presented below indicate that in many cases, a correlation between $\beta^{13}C$ and $\delta^{13}C$ values is observed.

For the first time the $\delta^{13}C$–$\beta^{13}C$ correlation was shown for components of lipid fraction (Galimov and Shirinski, 1975). The results are shown in Figures 2a–d. In all four cases the $\delta^{13}C$–$\beta^{13}C$ correlation exists. The analytical errors and uncertainty related to the approximate technique of evaluating the β-factor values contribute to the scattering. In spite of these sources of dispersion, the relationship

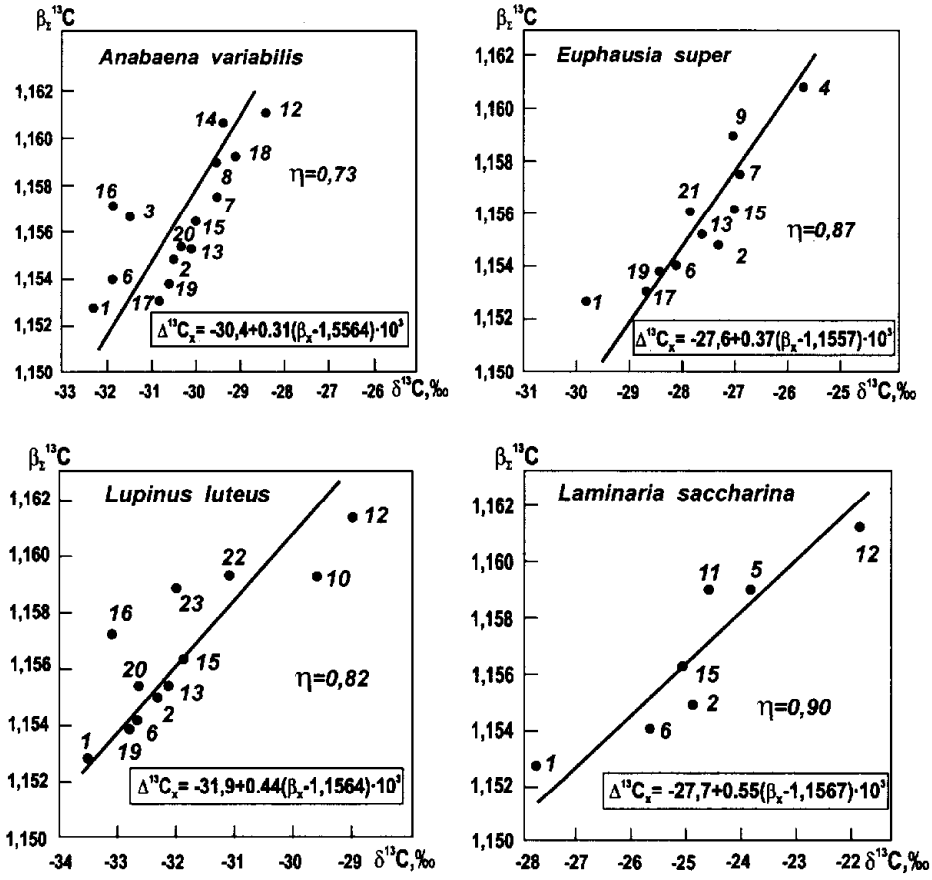

Figure 2. $\beta_{\Sigma}^{13}C$–$\delta^{13}C$ correlation of components of the lipid fraction of the blue-green alga (*Anabaena variabilis*), and krill (*Euphausia superba*), with $\eta = 0.73$ and 0.87, respectively; the lupine (*Lupinus luteus*) and the laminarian (*Laminaria saccharina*) with $\eta = 0.82$ and 0.90 respectively. 1. waxes, hydrocarbons, sterol, alcohols; 2. triglycerides; 3. *n*-carotene; 4. astatine; 5. carotenoid (fucoxanthine); 6. fatty acids; 7. carotenoid (echinenone); 8. sterol (β-sitosterol); 9. sterol (cholesterol); 10. sterol (β-sitosterol); 11. sterol (fucosterol); 12. chlorophyll; 13. diglycerides; 14. carotenoid (myxoxanthophyll); 15. monoglycerides; 16. phosphatidylserine; 17. sphingomyelin; 18. phosphatidylinositol; 19. lecithin; 20. cephalin; 21. cardiolipin; 22. pigment (lutein); 23. monogalactosylglyceride.

between $\beta^{13}C$ and $\delta^{13}C$ values is characterized by relatively high values of the correlation coefficients.

It is important to note that the regression equations contain a reducing coefficient æ before the term (in brackets) defining the thermodynamic isotope effect. The coefficient æ varies within 0.31–0.55 in the presented examples. This means that the biochemical reactions contain a component of reversibility. They are not in equilibrium, but are not far from equilibrium.

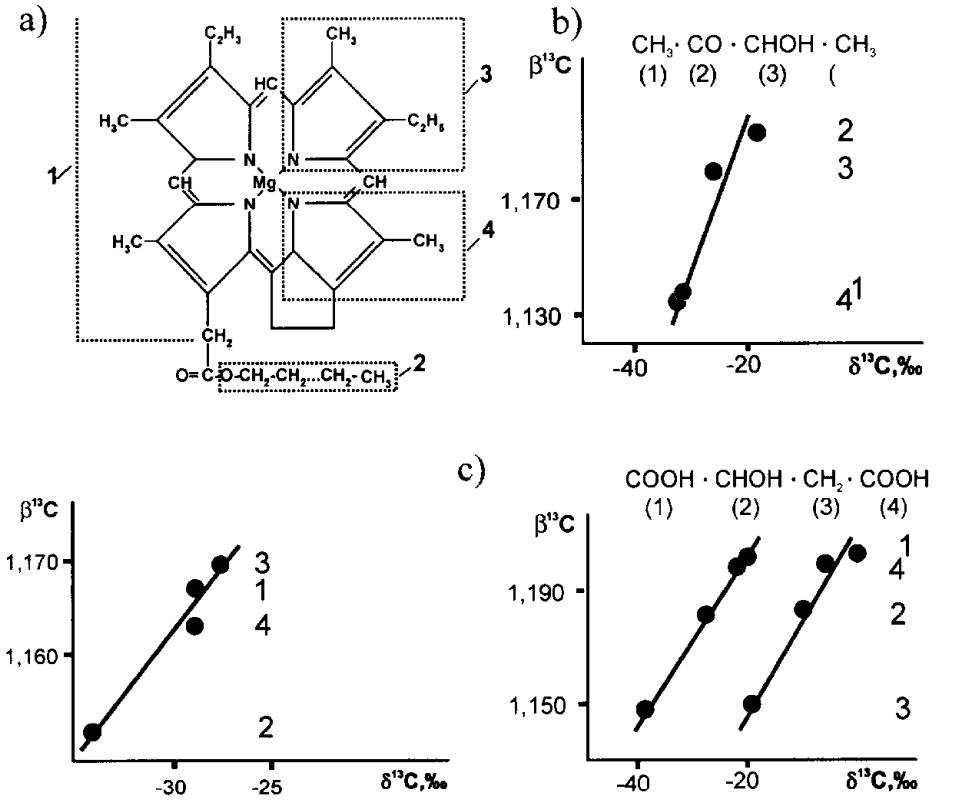

Figure 3. Intramolecular $\beta^{13}C$–$\delta^{13}C$ correlation: (a) intramolecular carbon isotope distribution in chlorophyll molecule, compared to $\beta^{13}C$-values of the corresponding fragments (Bogacheva, Galimov, 1979); (b) intramolecular carbon isotope distribution in acetoin molecule (experimental data by Rinaldi *et al.*, 1974) compared to $\beta_i^{13}C$-values related to the carbon atoms in the corresponding positions; (c) intramolecular $\delta^{13}C$-$\beta_i^{13}C$ correlation for malonic acid from C-3 plant (apple) an C-4 plant (sorghum) obtained by Meinschein *et al.* (1984).

Bogacheva and Galimov (1979) studied the intramolecular carbon isotope distribution in a chlorophyll molecule. A correlation was found between the measured values of $\delta^{13}C$ and the $\beta^{13}C$-factors evaluated for the corresponding fragments (Figure 3a).

W. Meinschein and coworkers from Indiana University studied intramolecular isotope effects in acetoin (Figure 3b) and malic acid (Figure 3c), and concluded: 'the ^{13}C contents of the specific carbon atoms in malic acid from apple and sorghum increase in accordance with their β values, as predicted by Galimov' (p. 346, Meinschein *et al.*, 1984).

During the last 10–15 years the most significant results in the field of the study of intramolecular isotope composition of biomolecules has been made by the group of H.-L. Schmidt from the Technical University in Munich. For the first time they

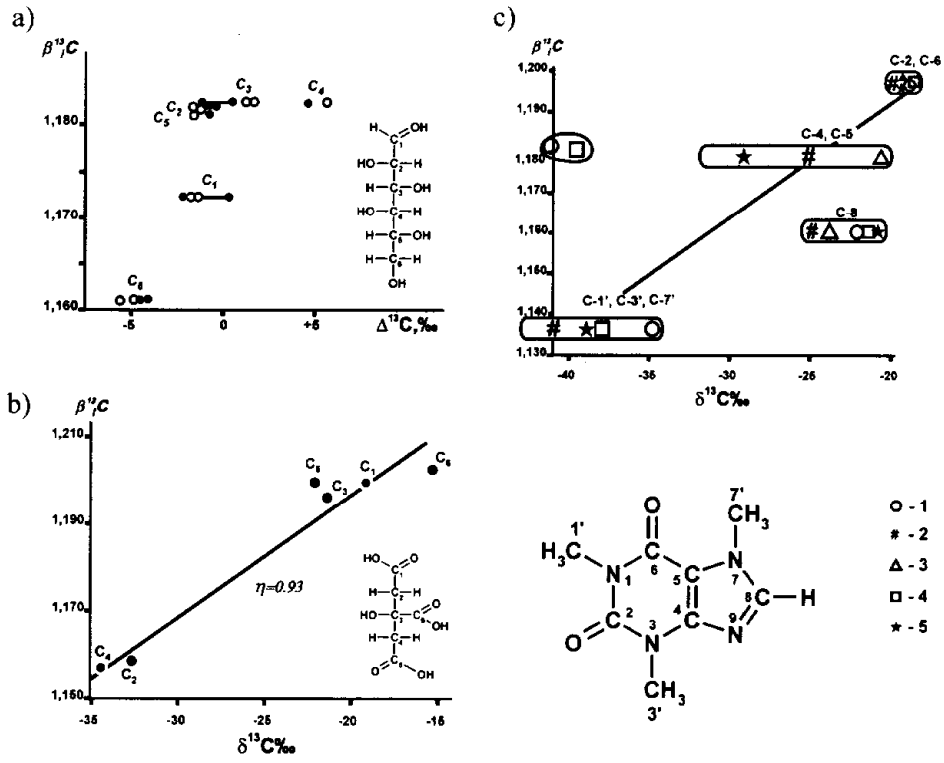

Figure 4. Intramolecular $\delta^{13}C$–$\beta_i^{13}C$ correlation: (a) glucose, extracted from C-4 plant maize (filled symbols) and C-3 plant beet (open symbols); the measured $\delta^{13}C$-values are adopted from Rossman *et al.* (1991); (b) citric acid; the measured $\delta^{13}C$-values from Schmidt, Gleixner (1998); (c) purine alkoloid (caffeine) from different geographical locations: 1 – Sri Lanca; 2 – Darjeeliny; 3 – Assam, 4 – China, 5 – U.S.S.R.; the measured $\delta^{13}C$-values from Weilacher *et al.* (1996).

measured the isotope composition of glucose at all six carbon positions (Rossman *et al.*, 1991). In this case the $\beta_i^{13}C$–$\delta^{13}C$ correlation proved to be not very good (Figure 4a). However, the correlation is obvious in other studied systems. In the case of citric acid (Schmidt, Gleixner, 1998) the correlation coefficient is $\eta = 0.93$ (Figure 4b).

Analysis of the complex caffein molecule (Figure 4c) has been made for preparations from different geographical locations (Weilacher *et al.*, 1996).

In Figure 5a data obtained by Gleixner *et al.* (1998) are presented for different biochemical compounds, extracted from leaves (filled symbols) and roots (open symbols) of potato. In Figure 5b the data for the amino acids from the same object are shown separately.

More examples could be presented. However, not all biochemical reactions necessarily must show such a relationship. Many processes in organisms are essentially irreversible and non-linear. The bad correlation in glucose is an example. The

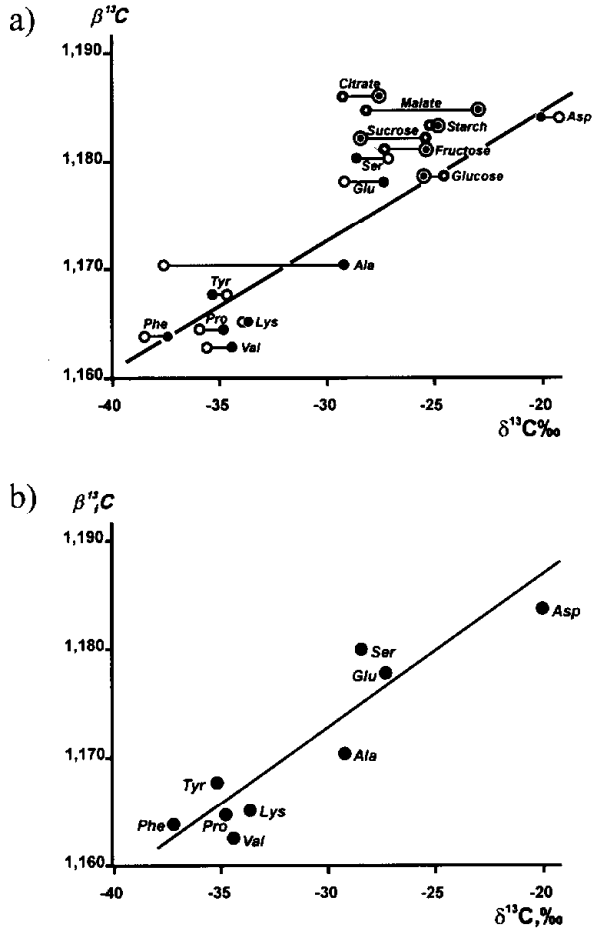

Figure 5. (a) $\beta^{13}_{\Sigma}C$–$\delta^{13}C$ correlation for organic compounds, extracted from potato leaves (●, ⊙) and roots (○, O). The measured $\delta^{13}C$ values are adopted from Gleixner *et al.* (1998); (b) $\beta^{13}_{\Sigma}C$–$\delta^{13}C$ correlation for amino acids extracted from leaves of potato. The $\delta^{13}C$-values from Gleixner *et al.* (1998).

correlation was not found in intramolecular distribution of carbon isotopes in fatty acids (Monson and Hayes, 1982). Nevertheless it is clear that the observed correlations are not accidental. The $\beta^{13}C$–$\delta^{13}C$ correlation is inherent to compounds of different structure, related to different biochemical components, observed in organisms of different taxonomy, from different environments, and manifested both at the intermolecular and intramolecular level. We will not go further into the discussion presented in the cited experimental works regarding possible particular causes of the observed isotope distributions. For us, the most interesting fact is that despite the many factors affecting isotope composition of biomolecules, the tendency to equilibrium isotope fractionation is clear.

Figure 6. Sequence of irreversible reactions, which at each stage have a reverse pathway, leading from product to the predecessor.

Fractionation of isotopes in a steady state system of enzymatic reactions has been considered earlier (Galimov, 1985). The reader is referred to this book for details. It has been shown theoretically that – under the assumption of microscopic reversibility of chemical transformations at the active center of an enzyme, and under steady state conditions – for isotope distribution in the metabolic chain depicted in Figure 6, the following expression is valid (see Galimov, 1985, pp. 146–148):

$$\delta_{k+n} - \delta_k = 1 + \overline{æ} \left(\frac{\beta_{k+n}}{\beta_k} - 1 \right) \pm \Sigma \Delta_k , \tag{12}$$

where δ_{k+n} and δ_k are isotope composition of carbon in k-th and $(k+n)$-th position within a given biological system; $\overline{æ}$ is reducing coefficient averaged over the pathway between k-th and $(k+n)$-th position; and $\Sigma \Delta_k$ is the algebraic sum of kinetic isotope effects in this pathway. The multiplier $\overline{æ}$ obeys the unequility: $0 < æ < 1$.

When æ is close to zero the biological effect is fully kinetic. This corresponds to an irreversible process, which is far from equilibrium (essentially non-linear). When æ is exactly equal to unity the complete equilibrium takes place. This is not characteristic of biochemical reactions. The case, when æ is between zero and unity, corresponds to a *steady state* process which is non-equilibrium but *not far from equilibrium*. The latter is described by the relationship similar to the experimentally observed $\beta^{13}C$–$\delta^{13}C$ correlations. Presence of kinetic isotope effects Δ_k results in deviations of the $\delta^{13}C$-values from the $\delta^{13}C$–$\beta^{13}C$ regression line. The $\Sigma \Delta_k$ accumulates also other sources of uncertainties.

Thus we can conclude from the isotope data that biochemical reactions often proceed not far from equilibrium. This confirms the validity of the presented model.

The preconditions of the model are disproportionation of entropy, energy supply, steady state and not-far-from-equilibrium conditions. In living organisms these features appear at the statistical level, as many processes occurring in organisms are completely irreversible and non-linear. However the isotopic data indicate that not-far-from-equilibrium reactions are inherent to biochemical systems, and that such reactions are reconcilable with biochemical behaviour. In other words, modern organisms are highly evolved entities which, however, show in their basis the same features as the simplest chemical systems must have had to start life.

Is a not-far-from-equilibrium state admissible for a system involving ATP conversion, which we suggested to be a key reaction providing ordering in the primitive world? In extant organisms, energy transfer by the use ATP hydrolysis and restoration of ATP by phosphorylation is a complex process controlled by enzymes. In a simple ATP-ADP reaction, proceeding in water medium, the equilibrium is

significantly shifted towards ATP hydrolysis. The concentration of ATP in the absence of effective mechanisms for resynthesis is extremely low. However ATP-ADP conversion could proceed under conditions of limited access of water to the reaction site, for example, when the process is located at hydrophobic films, proceeds at inner surface of microbubbles, and so forth. Then a steady state of the conjugated reactions of ATP-hydrolysis, on one hand, and synthesis of a bond (e.g. peptide bond or linkage between nucleotides) on another, can be established. The driving force of the process is phosphorylation. It determines the flux of energy into the system. In fact, it may proceed beyond the system (for example, by light exitation). However the ATP $\leftrightarrows$ ADP conversion in the system can not be far from equilibrium, and conjugation with the reaction of synthesis keeps the machinery of disproportionation of entropy working.

It is not the purpose of this paper to consider evolution of this system, including different scenarios of phosphorylation. It should just be stressed again that the first step of evolution was the synthesis of polymeric compounds, initially very primitive, which nevertheless provided selectiveness of chemical interactions, or ordering. This increasing ordering made the systems, evolving by this way – eventually biological systems – irrecognizably complicated. However, the ability to produce ordering, while not far from equilibrium (but at steady state conditions!), has been preserved as a fundamental property of biological systems.

It follows from the above stated that living systems occupy a narrow niche of states of matter. These are iterative steady state systems of irreversible processes, proceeding in the linear field of dependencies of forces and flows. Chemical equilibrium is death. Life is a permanent fight against the tendency to equilibrium. On the other hand, non-linearity in an iterative system leads ultimately to the accumulation of errors and finally to the end of the process of ordering (chaos), to death. The field of linear iterative processes is the realm of life.

5. Conclusions

- A model is presented that describes the processes of ordering as the indispensable result of disproportionation of entropy in a steady state system of microscopically conjugated reactions.
- This ordering is comprehended as a consecutive restriction of freedom: freedom of motion, interactions etc., via the production and evolution of catalysts.
- It is argued that a chemical system which meets the demands of the physical model may include ATP as a key molecule of prebiotic evolution, since ATP hydrolysis is microscopically conjugated with synthesis of polypeptides and polynucleotides.
- The model presented suggests microscopic ordering. Transformation of the microscopic ordering to the macroscopic level requires a mechanism of self-

reproduction (iteration). Evolution has resulted in the creation of a coupling of iteration and catalysis via the genetic code.

– It is shown by use of isotope data that biochemical systems act not far from equilibrium. This makes it possible to apply the theoretical approach of linear thermodynamics of irreversible processes.

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