# Spontaneous breaking of mirror symmetry in nature and the origin of life

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The current state of the problem of the breaking of mirror symmetry in the organic medium in the course of the appearance of life is reviewed. A detailed analysis of the data available leads to the conclusion that the stage in which the various components of the future biopolymers (amino acids, sugars, etc.) formed and accumulated in racemic form must have been followed by a stage of a strong breaking of mirror symmetry and a deracemization of the organic medium. The deracemization process was a cooperative, bifurcation process. Analysis shows that the sign of the chiral polarization of the biosphere (L-amino acids, D-sugars) was the result of a "memory" of a random selection in the course of a bifurcation, rather than a consequence of parity breaking in weak interactions. The possibilities of a breaking of mirror symmetry in the "warm" (terrestrial) and "cold" (extraterrestrial) scenarios of the origin of life are analyzed. The model of a destruction of the biosphere as a result of long-term global racemizing perturbations is also discussed.

**CONTENTS**



## 1. INTRODUCTION

It has been more than a hundred years since Louis Pasteur's discovery of a "demarcation line" between life and nonlife: the mirror dissymmetry of organisms.[1] It might seem that over such a length of time essentially any field of research (including this one) would have been exhausted. However, the fact that living organisms use only one of the two mirror isomers of such molecules as amino acids and sugars, while making absolutely no use of the other isomer (only the D isomers or sugars are found in nucleic acids, and only the L-isomers of amino acids are found in enzymes), remains an intriguing puzzle.

This phenomenon—the breaking of mirror symmetry in the molecular basis of life—is apparently the first and one of the clearest examples of a symmetry breaking in natural science. The interest in this problem, which might itself appear to be purely biological, has arisen more from chemistry and physics than from biology. P. Curie,[2] Lord Kelvin,[3] P. Jordan,[4] E. Fisher,[5] J. Bernal[6] and many others have paid tribute to this problem.

Before we begin our discussion of the present state of the problem of the breaking of mirror symmetry in living nature or, more precisely, at the molecular level of living nature, however, we would like to recall for the reader some of the basic concepts which we will be using below.

Entities which do not have a center and an inversion plane are called "chiral" (or "mirror-antipodal"). If such an object is reflected in a mirror, the result is an object which is spatially nonsuperimposable with the original object, just as the left hand and the right hand. This is, by the way, the origin of the term "chirality": The Greek word for "hand" is χειρ. The term itself was introduced in science by Lord Kelvin. Among chiral objects are, in particular, molecules which contain a so-called asymmetric carbon atom: amino acids, sugars, etc. These molecules have the property of chirality in the case that if all four substituents (ligands) which are bound to the central carbon atom are different (Fig. 1). Mirror isomers (enantiomers) of such molecules are usually called *levo* and *dextro* isomers and are designated in the biophysical literature by the letters L (from *laevo*, "left") and D (from *dextro*, "right"). We will be using these symbols below. (In the chemical literature, the so-called R, S-nomenclature recommended by the IUPAC is more common for designating mirror isomers.) Mirror isomers are remarkable in that substances which are formed exclusively by L-isomers or exclusively by D-isomers (e.g., solutions and crystals) have identical physical properties: an identical in-

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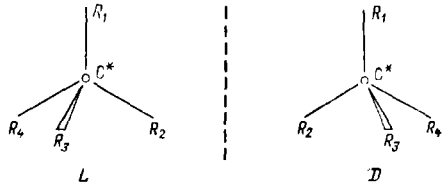


FIG. 1. Mirror isomers (L and D) of a molecule with an asymmetric carbon (C) atom.

ternal energy, an identical solubility, an identical melting point, an identical boiling point, etc. The only physical distinction between them is that these substances rotate the polarization plane of light passing through them in opposite directions; i.e., they have an optical activity. The chemical properties exhibited by mirror isomers as they interact with nonchiral molecules are also identical. We might note that phosphorus and nitrogen atoms could also serve as the asymmetric center, instead of carbon. We know of molecules whose chirality stems not from the presence of some asymmetric center (atom) but from the spatial structure[7], e.g., biphenyls (Fig. 2), which have a "propeller" structure. From the standpoint of the problem of the breaking of mirror symmetry in the molecular basis of life, however, the sugars and the amino acids are of primary interest.

Chiral purity in contrast with the chirality of an individual small molecule (such as an amino acid or sugar molecule), is a property of an object (a macromolecule—a protein or a nucleic acid—or a medium consisting of isomer molecules) formed by chiral molecules. This property is that such an object contains molecules of only one chirality type (either L or D). If an object contains equal numbers of mirror antipodes, it is "racemic."

In nonliving nature, *levo* and *dextro* molecules are present in equal numbers, but in living nature we observe a marked disbalance between the *levo* and *dextro* isomers: As we have already mentioned, the molecular basis of life is chirally pure. Chiral purity, along with a genetic code which is common to all life on earth, is thus a distinguishing and crucial property of living things.

No scenario for the origin of life could be constructed without solving the question of the mechanism for the arising of chiral purity (or, as it is also phrased, the "breaking of mirror symmetry"). For this reason, attempts to find an answer to this question have been made continuously for more than a century now. Another reason for the unflagging interest in this problem is that the chiral purity of biopolymers is a necessary condition for their normal functioning. It is for this reason that the question of the origin of this property becomes one of the crucial questions for reaching an understanding of the processes which lead to the formation of self-reproducing biological systems.

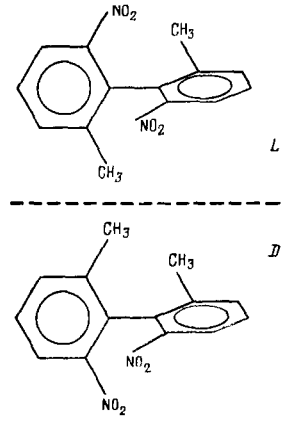


FIG. 2. Mirror isomers of a substituted biphenyl. The chirality results from the "propeller-shaped" structure of the molecule.

Until recently, one could distinguish two basic approaches to the solution of the problem of the arising of chiral purity. The first approach started from the idea that this property is biogenic: Isomers of one type were selected in the course of the vital activity of the first organisms.[9] It is assumed here that chirally pure initial organisms constructed from the same isomers as modern organisms had some evolutionary advantage over racemic organisms, i.e., organisms made up of a racemic mixture of isomers, and won the struggle for existence. That approach, however, runs into some fundamental difficulties, which we will discuss in §2.

The second approach starts from the idea of an abiogenic path for the appearance of chiral purity in a prebiological, chemical stage of evolution as a result of physicochemical processes in a "primeval soup."

One can choose between these two approaches by resolving the "auxiliary" question of whether the property of self-replication of molecular structures (such as protonucleic acids) would be possible in a racemic medium. If it is possible, the version of a biogenic chiral purity would be permissible; if it is not possible, the breaking of mirror symmetry is not biogenic. The analysis of this question is the basic content of §2.

Along the abiogenic approach, two paths have developed for solving the question of the appearance of chiral purity. One path links the breaking of mirror symmetry of the organic medium with an effect of some asymmetric factor which had conferred an advantage on mirror isomers of one type. A gradual "buildup" of this advantage resulted in the dominance of this type of isomer. This scenario for the breaking of mirror symmetry might be called the "sequential evolution scenario" or simply the "evolutionary scenario." This approach is discussed in §5.

A completely different path for the appearance of the chiral purity of the organic medium is seen in the scenario of a spontaneous breaking of mirror symmetry in a chemical-evolution stage. The essence of this path is that the deracemization of the protobiosphere is linked not with some asymmetric external agent but with a self-organization of chirality in a primeval soup. An initially racemic mixture attains chiral purity through a nonequilibrium "phase transition." Note that this scenario is based on not only a theoretical analysis of the kinetics of processes in nonequilibrium chiral systems (§4) but also the experimentally observable cooperative nature of the behavior of even slightly viscous solutions of mirror isomers.[9-12] The scenario of a spontaneous breaking of mirror symmetry is discussed in §6. In the same section we analyze the question (presently the subject of an active discussion) of whether weak asymmetric agents can be amplified by systems with a spontaneous breaking of mirror symmetry. The interest in this problem stems primarily from the hypothesis of a relationship between the deracemization of the prebiosphere and parity breaking in the weak interactions of elementary particles.

Treating the process by which the prebiosphere was deracemized as a "phase transition," we can evaluate the physical conditions which would be required for reaching chiral purity. In particular, we can estimate the time at which we would expect an irreversible breaking of mirror symmetry to begin. This question is discussed in §7.

There has recently been a revival of interest in "extraterrestrial" scenarios for the origin of life on earth. This interest has stemmed, on the one hand, from the discovery of some fairly complex organic compounds (ranging up to amino acids) in space, with the implication that the synthesis of such molecules also occurs under conditions which are quite extreme from the standpoint of terrestrial chemistry.[13,14] On the other hand, impressive geological discoveries of recent years definitely indicate that a quite developed biosphere existed on the earth as early as $3.5 \cdot 10^9$ to $3.8 \cdot 10^9$ yr ago.[15,16] Since the origin of life would have been possible only after the formation of a solid crust on the earth, which occurred $4 \cdot 10^9$ yr ago, the duration of the prebiological stage of evolution could not have exceeded $0.2 \cdot 10^9$ to $0.5 \cdot 10^9$ yr. Such severe time limits on the process by which life arose, bracketing the period from the formation of the primeval soup containing all the necessary "building blocks" of life to protocells and primitive organisms, have caused some researchers to doubt the validity of the "standard model" of the origin of life, i.e., the Oparin-Haldane theory.[17-19] Note, however, that the hypothesis of an extraterrestrial origin of life, which dates back to the "panspermia" theory of Arrhenius,[20] does not by itself eliminate the fundamental question here: the question of the processes capable of giving rise to the crucial properties of life, primarily the chiral purity of the organic medium. The hypothesis of a "cold prehistory of life" must be analyzed from this standpoint. The possibilities for a breaking of mirror symmetry in this version are discussed in §8, where we focus on the "stabilization" of the chirality under low-temperature conditions (such that chemical reactions go by a tunneling mechanism).

Finally, in §9 we discuss the possibility of a destruction of the chiral purity of the biosphere under the influence of long-term racemizing influences.

This review is thus devoted primarily to the physical aspects of the problem of the breaking of mirror symmetry in the course of a prebiological evolution of the organic medium. We believe that appealing to physical ideas and methods to solve this problem not only leads to a deeper understanding of the actual problem of the appearance of the chiral purity of the biosphere but also makes it possible to analyze the processes which determined the course of the process by which life arose.

## 2. CHIRAL PURITY AND SELF-REPLICATION

The biogenic scenario for the arising of chiral purity implicitly assumes that the functioning of an information carrier—a nucleic acid molecule—does not depend in a fundamental way on the chiral composition of its primary sequence. Let us examine this question in more detail. We know that the DNA molecule is a double-stranded structure whose primary sequence is formed by nucleotides (phosphate group + sugar molecule + nitrogenous base) (Fig. 3). The strands are connected to each other in accordance with a complementarity rule: Each of the four nitrogenous bases—adenine (A), guanine (G), thymine (T), and cytosine (C)—forms bonds only with the base which is complementary to itself, specifically, A–T and G–C. We have already mentioned that only the D-isomers of sugar molecules are used in nucleic acids. Is there a relationship between the chirality of sugars and the complementarity of the double helix of a nucleic acid? This question was answered in Refs. 21 and 22.

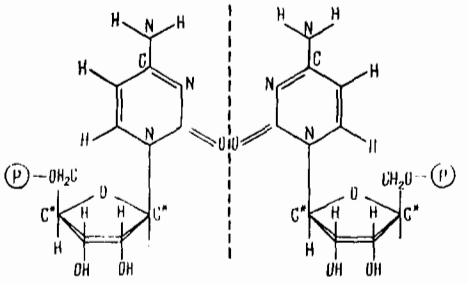

FIG. 3. Mirror isomers of a nucleotide. The sugars have opposite chiralities.

It seems almost obvious that the replacement of a single natural D-nucleotide (i.e., a nucleotide which contains the D-isomer of a sugar molecule) in a double-stranded structure (e.g., DNA) by its mirror-image L-isomer will lead to the formation of a structure with a higher energy. However, will the complementarity of a chirally defective pair of this sort be retained in the double-stranded structure? Furthermore, will such a defect turn out to be a local defect, or will it disrupt a large region of the double-stranded structure? Qualitative answers to these questions can be found by constructing a molecular model of the situation. The most suitable models for this purpose are the Corey-Pauling-Coltun molecular models.

For a comparison, two fragments of a double-stranded structure, each containing five A–T complementary pairs, were constructed. The nucleotide strands of each fragment contained only one type of nucleotide (poly-A strands and poly-T strands, respectively. These fragments serve as models of a polynucleotide chain which is characteristic of DNA (or of RNA, if the T-base—thymine—is replaced by the U-base uracil—and if the deoxyribose is replaced by ribose).

In the first fragment, each of the filaments was chirally pure. The structure of the fragment was of course regular (Fig. 4), and results in a fragment of the so-called B-form of

FIG. 4. Homochiral double-stranded A–T structure.

FIG. 5. Fragment of a double helix: poly-A–poly-T.

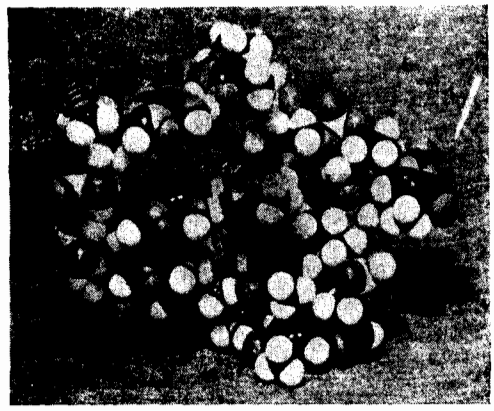

FIG. 7. Fragment of a double helix with a chiral defect.

the usual double helix (Fig. 5). The second fragment differed from the first in that the T-nucleotide in the third unit was replaced by its mirror-image isomer (i.e., the D-sugar was replaced by an unnatural L-sugar). Such a nucleotide was introduced into the structure in such a way that the poly-T strand was not broken (Fig. 6). This structure models a chiral defect in a polynucleotide chain.

Figure 7 shows the B-form containing a chiral defect. In such a structure, the pyrimidine ring of the "defective" T-nucleotide has been swung through an angle $\sim 100°$ from the normal position of the nitrogenous base in the double helix. Hydrogen bonds thus cannot form between the A- and T-bases of the defective pair, so we lose the main reason for the appearance of the A–T complementarity (and also for the G–C or A–U complementarity, for RNA), since in this case the combination of the bases of the nucleotides of the defective pair can be arbitrary. The situation remains the same when we look at yet another shape of the double helix which is encountered, the so-called A-form, containing a chiral defect.

It is not difficult to see that when one unit (one pair of nucleotides) is incorporated in a homochiral double-stranded structure the chirality of the two partners is always opposite that of the remaining nucleotides. Again in this case, a foreign pair cannot be incorporated in the structure.

Chiral purity of polynucleotides is thus a necessary condition for complementarity.

In the absence of enzymatic replication mechanisms (which are characteristic of modern organisms), this problem becomes extremely pertinent. In particular, the formation of a chiral defect can occur in the process of matrix oligomerization. It is extremely likely that an abiogenic formation of polynucleotides of this type was characteristic of the conditions prevailing during the prebiological evolution.[23] This process is of considerable interest, especially since the discovery that RNA exhibits an autocatalytic activity and is capable of self-replication even in the absence of a special enzymatic apparatus.[24,25]

FIG. 6. Double-stranded structure with a chiral defect.

After it has been established that there is an unambiguous relationship between complementarity and the chiral purity of polynucleotide chains, however, we are confronted with another question. Let us assume that a single chirally pure polynucleotide chain (proto-RNA) has formed by chance in a racemic medium. Will it be capable of replicating itself in such a medium through a process of matrix oligomerization?

Experiments were carried out in 1984 to determine how the chiral composition of a medium affects the process of matrix oligomerization.[26–28] Those experiments can be summarized as follows. Some polynucleotide chains which had been synthesized (the matrices) were placed in a solution of monomer nucleotides, which was chirally pure in one case and racemic in another. After a certain time, a study was made of the result of the process of matrix oligomerization of the nucleotides on the matrices. In other words, the length of the chirally pure "replicas" was studied as a function of the chiral composition of the monomer medium.

It was found in those experiments that the process by which a complementary chain is assembled on a chirally pure matrix is greatly suppressed if the solution of monomers is racemic. This result can be understood quite easily by taking account of the relationship between the chirality of polynucleotides and their complementarity. Furthermore, experiments of this type make it possible to construct a qualitative model which relates the replication process to the chiral composition of the medium.[29,30]

We assume that in a medium with a chiral polarization[31] $\eta = |(L - D)/(L + D)|$ ($L$ and $D$ are the amounts of *levo* and *dextro* monomers in the medium; for a racemate we would have $\eta = 0$, while for a chirally pure medium we would have $|\eta| = 1$) a certain number of chirally pure polynucleotides of length $n$ have arisen by chance. As we have already seen, a necessary condition for the complementarity of each unit of the original matrix and of the replica is that

the nucleotides which enter these units in pairs (e.g., A–T and G–C pairs) be of identical chirality. We then see that a necessary condition for the formation of a replica of any substantial length, for any value of $n$, is that the original polynucleotide matrix be chirally pure (in the $\eta = 1$ case, this condition is set by the initial condition itself, while in the case $\eta \neq 1$ it is a consequence of the exponential suppression which was demonstrated in Refs. 26 and 27). For simplicity we will stop drawing a distinction between the replica and the original matrix (as we are justified in doing since the replica itself becomes the matrix in the next step). We introduce a rate constant $K_n^+(\eta)$ of the replication of the polymers of length $n$ in a medium with a chiral polarization $\eta$, and we also introduce a decay rate constant of these polymers, $K_n^-(\eta)$. By the "decay" of a chirally pure polynucleotide we mean not only its destruction but any process which has the consequence that the polymer loses the self-replication property, e.g., the appearance of a unit with a monomer of the antipodal chirality in the polymer chain. We write a kinetic equation for the number ($x_n$) of chirally pure polymers of length $n$ in the following form:

$$\frac{dx_n}{dt} = (K_n^+(\eta) - K_n^-(\eta))\, x_n. \tag{1}$$

We say that the replication process is "stable" if $dx_n/dt > 0$ ($x_n$ increases with the time) or "unstable" if $dx_n/dt < 0$.

To analyze the problem of the stability of the self-replication of polymers of length $n$ in a medium with a chiral polarization $\eta$, we need to know how the replication rate constant and destruction rate constant of the polymers depend on these parameters. We would naturally expect that at a fixed value of $n$ the time scale for the assembly of a replica on a matrix will increase, at least at $n > n'$. Consequently, $K_n^+(\eta)$ must be a decreasing function of $n$. On the other hand, we would expect that at a fixed value of $n$ the constant $K_n^+(\eta)$ would decrease with a decrease in the chiral polarization of the medium. These arguments are based on the experimental results of Refs. 26 and 27. The distributions of the chirally pure polynucleotides which build up over the course of an experiment with respect to their length $n$ (Fig. 8) can be interpreted as the probability distribution for the formation of such polymers in a medium with a certain value of the chiral polarization $\eta$. It is easy to see that the distributions of chirally pure replicas depend extremely strongly on both the length of the replica and the chiral purity of the composition of the medium. These distributions can be approximated, at least starting at a certain value of $n$, by the exponential distribution[29,30]

$$P(n, \eta) = \frac{x_n(\tau)}{\tau} \sim e^{-\alpha(\eta)n}$$

with an exponent $\alpha$ which decreases with increasing $\eta$[$x_n(\tau)$ is the number of oligomers of length $n$ which are formed during the duration of the experiment, $\tau$, in a medium with a chiral polarization $\eta$]. On the basis of these results, the rate constant of the replication process which we introduced above [see Eq. (1)] can be found from

$$K_n^+(\eta) = f(t)\frac{dx_n}{dt} \approx C_\eta(n, \tau)\frac{x_n(\tau)}{\tau};$$

here $C_\eta(n,\tau)$ is a factor which links $K_n^+(\eta)$ with the experimental values of $x_n(\tau)/\tau$ [for a polycondensation process, $C_\eta(n,\tau)$ would be a nonincreasing function of $n$]. For the

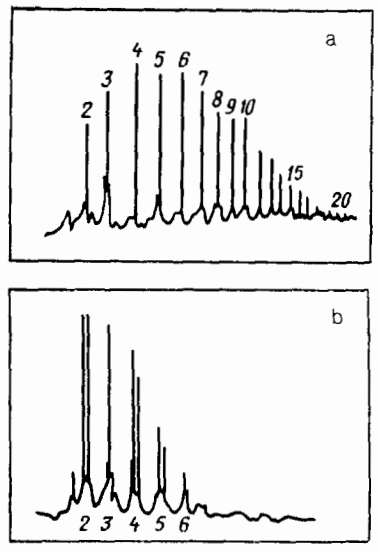


FIG. 8. Distribution of replicas synthesized on a chirally pure matrix. a—Replication in a chirally pure solution of nucleotides; b—replication in a racemic solution of nucleotides.

dependence of $K_n^+(\eta)$ on $n$ and $\eta$ which we have introduced, we can thus choose a very simple interpolation of $K_n^+(\eta)$ using a linear dependence of $\alpha$ on $\eta$:

$$K_n^+(\eta) = A_n \exp[(\alpha_0 - \alpha_1)\, n\eta], \tag{2}$$

where $\alpha_0 \equiv \alpha(\eta = 0), \alpha_1 \equiv \alpha(\eta = 1)$, and $A_n = A \exp(-\alpha_0 n)$ is the rate constant of the replication of a polymer of length $n$ in a racemic medium.

For $K_n^-(\eta)$ we can use the following very simple approximation: $K_n^-(\eta) = K^- = \text{const}$. This approximation corresponds to the assumption that the decay time of the polymer ($\tau_d = 1/K^-$) depends on neither the length of the polymer nor the chiral polarization of the medium, $\eta$. Since $K_n^-(\eta)$ should generally increase with increasing $n$ as well as with decreasing $\eta$, incorporating the dependence of $K^-$ on these quantities could only reinforce the results derived below. It follows from (1) and (2) that the replication of chirally pure polymers of length $n$ in a medium with a chiral polarization $\eta$ is a stable process if

$$K_n^+(\eta) = A_n \exp[(\alpha_0 - \alpha_1)\, n\eta] > K^-,$$

i.e.,

$$\eta > \frac{\ln(K^-/A) + \alpha_0 n}{(\alpha_0 - \alpha_1)\, n} \equiv \eta_n^{cr}. \tag{3}$$

Note that if the relation $\eta_n^{cr} > 1$ holds for any values of $\alpha_0, \alpha_1, K^-, A$, and $n$ the meaning is that the replication of polymers of length $n$ is an unstable process in a medium with an arbitrary chiral polarization, since the relation $|\eta| \leqslant 1$ holds by virtue of the definition of $\eta$. We also note the weak (logarithmic) dependence of $\eta_n^{cr}$ on a variation of the decay rate constant $K^-$ and the considerably stronger dependence on the length of the polymer, $n$.

Let us estimate the quantity $\Delta\eta_n^{cr} = 1 - \eta_n^{cr}$, which describes the deviation of $\eta_n^{cr}$ from the polarization of a chirally pure medium. From (3) we find

$$\Delta\eta_n^{cr} = \frac{(1/n)\ln(A/K^-) - \alpha_1}{\alpha_0 - \alpha_1}. \tag{4}$$

Relation (4) shows that as the polymer gets longer the

"gap" $\Delta\eta_n^{cr}$ becomes progressively narrower: A progressively closer approximation to a chirally pure medium is necessary for stable replication of longer polymers. It also follows from (4) that there exists a certain length $n_{max}$ above which a polymer is no longer capable of stable replication. For all polymers of length $n > n_{max}$, the replication process is unstable, even in a chirally pure medium. The quantity $n_{max}$ can be found by setting $\Delta\eta_n^{cr} = 0$ in (4):

$$n_{max} = \frac{1}{\alpha_1} \ln \frac{A}{K^-}.$$

The upper limit on $n_{max}$ can be found easily by using rough estimates of the parameters $\alpha_0$, $\alpha_1$, and $A$ which can be extracted from the experimental data reported in Refs. 26 and 27 for polynucleotides ($\alpha_0 \sim 3$, $\alpha_1 \sim 10^{-1}$, $A \sim 10^{-5}$ $s^{-1}$) and by assuming that the decay time of these polymers, $\tau_d$, is comparable to the age of the earth. In other words, we adopt the value of $K^- \approx 10^{-17}\ s^{-1}$, which is obviously too low. As a result we find $n_{max} \sim 3 \cdot 10^2$. Longer polynucleotides cannot replicate stably even in a chirally pure medium. Chirally pure polymers with $n > 300$ which are capable of replication apparently appeared even in the later stages of the prebiological evolution, as a result of an interaction of chirally pure polynucleotides of length $n \sim 300$ with spectrally pure oligopeptides and/or polypeptides (and, possibly, protoenzymes). We wish to stress that the length of the polymers which are capable of stable replication falls off rapidly with decreasing $\eta$, and in a racemic medium its value is only $\sim 10^1$ (even with our value of $K^-$, which is clearly too low).

These qualitative estimates, combined with the rigid relationship which has been established between the chiral purity of polynucleotides and their property of complementarity, let us proceed to the conclusion that even the simplest self-replicating systems could have appeared only in a medium in which there was a pronounced breaking of mirror symmetry—essentially only in a chirally pure medium. Consequently, it was in the prebiological stages of evolution that the physicochemical processes which led to the global breaking of mirror symmetry of the organic medium must have occurred.

It can be concluded from these results that the biogenic scenario for the onset of the chiral purity of the biosphere could not, even in principle, have been realized in the course of evolution, since without chiral purity of the medium the apparatus of self-replication could not appear. This apparatus is a basic process in the self-reproduction of any organism. Life cannot arise in a racemic medium.

Furthermore, we cannot accept scenarios in which the chiral purity of the prebiosphere is linked with a selection step in the stage of the formation and selection of the predecessors of the most important biopolymers. As was shown above, the process by which they form and accumulate could not occur in a racemic medium.

We are thus left with the abiogenic scenario as the only realistic scenario for the appearance of chiral purity. The following sections of this review contain a detailed analysis of various aspects of this approach to the problem of the breaking of mirror symmetry.

## 3. RACEMIZATION, HUND'S PARADOX, AND THE DERACEMIZATION PROBLEM

For a long time it was believed that any chemical transformations which result in the formation of chiral molecules, as well as transformations of the chiral molecules themselves, could lead to only a racemic mixture of these molecules. The most common arguments can be reduced to the following form. We consider a reaction in which a chiral molecule is formed from an achiral molecule, specifically, a reaction in which one of the two identical ligands Y in a tetrahedron of chemical bonds is replaced by a ligand R (Fig. 9). It is totally obvious that the ligands Y are equivalent and that the replacement of either of the ligands in this reaction is equiprobable. Consequently, the result is the formation of a racemic mixture of L- and D-isomers.

It is also easy to see that under symmetric conditions (in an isotropic space) the thermodynamic potential $F$ of a system of mirror isomers with concentrations $x_L$ and $x_D$,

$$F = Nk_BT\,(x_L \ln x_L + x_D \ln x_D) - u\,(x_L + x_D)$$

reaches its minimum in the case of a racemic mixture ($x_L = x_D$), since in this case the mixing entropy is at a maximum ($u$ is the internal energy of the isomer molecules). Consequently, even if one of the isomers was present in excess initially, sooner or later the chemical transformations

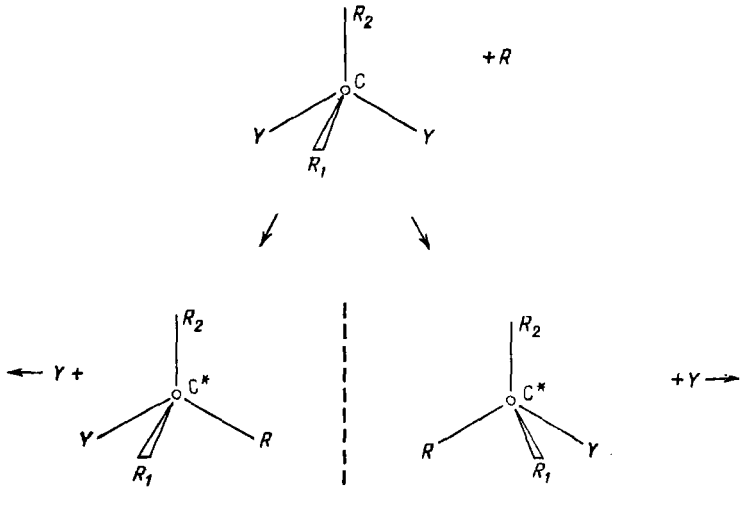


FIG. 9. Reaction in which a chiral molecule is formed from an achiral predecessor.

TABLE I. Time scales of the racemization of amino acids.

| Amino acid | Temperature, °C | pH of medium | Racemization "half-life," yr |
|---|---|---|---|
| Alanine | 0 | 7 | $1{,}4\cdot10^{6}$ |
| | 25 | 7 | $1{,}2\cdot10^{4}$ |
| Asparaginic acid | 0 | 7 | $4{,}3\cdot10^{5}$ |
| | 25 | 7 | $3.5\cdot10^{3}$ |
| Valine | 135 | 7 | 0,25 |
| | 135 | 0,9 | 1,33 |
| Isoleucine | 0 | 7 | $6\cdot10^{6}$ |
| | 25 | 7 | $4{,}8\cdot10^{4}$ |
| | 100 | | 1,6 |
| | 200 | | $5\cdot10^{-5}$ |
| Phenylalanine | 0 | 7 | $1{,}6\cdot10^{5}$ |
| | 25 | 7 | $2\cdot10^{3}$ |

would bring the system to a racemic state, which corresponds to thermodynamic equilibrium. The system racemizes itself, as it is said.

The racemization process (or the inversion of the antipodes) can be represented by the reaction

$$\mathrm{L} \underset{\longleftarrow}{\overset{k_r}{\longrightarrow}} \mathrm{D}, \tag{5}$$

where $k_r$ is the racemization rate constant. This model describes not only the direct inversion of antipodes but also other processes which effectively reduce to model (5). At temperatures of the order of room temperature (and above), racemization occurs as the result of an above-barrier transition. In other words, it results from thermal excitations. A racemization process can also be induced, e.g., by radiation, in which case we would speak in terms of "photoracemization" or "radiation racemization." The time scale of racemization depends very strongly on the external conditions (the temperature, the pH of the medium, the presence of heavy-metal ions in the medium, etc.).[32-36] Table I shows some experimental data on racemization. Note that as early as 1927 Hund[37] pointed out that racemization is—speaking somewhat loosely—inherent in chiral molecules. The situation is that mirror isomers constitute states which are degenerate in energy from the quantum-mechanical standpoint (Fig. 10), so they are not eigenstates of a molecule, since the L- and D-states have a chirality but do not have a definite parity. Eigenstates of the molecule which are capable of existing in two mirror-isomer forms are symmetric and antisymmetric combinations of the states $|+\rangle$ and $|-\rangle$:

$$|+\rangle = \frac{1}{\sqrt{2}}(|\mathrm{L}\rangle + |\mathrm{D}\rangle),$$
$$|-\rangle = \frac{1}{\sqrt{2}}(|\mathrm{L}\rangle - |\mathrm{D}\rangle). \tag{6}$$

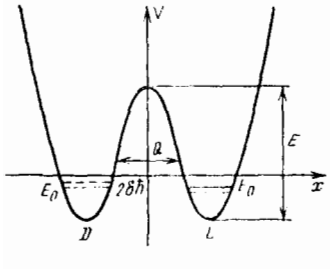


FIG. 10. Chiral molecule as a two-level system. $x$—Collective coordinate of molecules: $E$—height of the barrier separating the L- and D-states; $Q$—width of barrier.

These states have a definite parity but not a chirality. Consequently, the molecule "oscillates" between the L- and D-states through a tunneling with a characteristic frequency

$$\Omega = \tau^{-1} \exp\left[-(2ME)^{1/2}\frac{Q}{\hbar}\right], \tag{7}$$

where $M$ is the mass of the molecule, $E$ is the height of the energy barrier separating the L- and D-states, $Q$ is the width of this barrier, and $\tau$ is a time scale of the intramolecular motions. Accordingly, if the molecule is initially in, say, the L-state then after a time $T = \Omega^{-1}$ it will be in the D-state. Consequently, over a time $t \gg T$ the probability for finding a molecule in the L-state will be the same as that for finding it in the D-state, 1/2. This result means that the system of isomers racemizes itself over a time $t \gg T$.

Racemization processes prevent a breaking of mirror symmetry, tending to restore the system to a racemic state. Consequently, a deracemization could have occurred only if processes capable of effectively countering the tendency toward racemization exist.

## 4. BASIC TYPES OF PROCESSES IN CHIRAL SYSTEMS

Let us assume that we have a system containing chiral molecules (L and D, with concentrations $x_L$ and $x_D$) and achiral molecules (with concentrations $x_A, \ldots$) which are capable of undergoing various chemical transformations. The kinetics of reactions which lead to a change in the concentrations of chiral molecules is described by the equations

$$\frac{dx_L}{dt} = f_L(x_i;\ \{k_i\}),$$
$$\frac{dx_D}{dt} = f_D(x_i;\ \{k_i\}), \tag{8}$$

where $x_i = (x_L, x_D, x_A, \ldots)$, and $\{k_i\}$ is the set of reaction rate constants. Models of chiral systems are usually expressed and studied in terms of the variables $x_L$ and $x_D$. As was shown in Refs. 31 and 38, however, the dynamics of chiral systems can be studied considerably more conveniently in terms of some other variables: the "chiral polarization"

$$\eta = \frac{x_L - x_D}{x_L + x_D}$$

and the "dimensionless concentration of antipodes" in the system,

$$\theta = \nu(k_i, x_A, \ldots)(x_L + x_D),$$

where $\nu(k_i, x_A)$ is a coefficient which depends on the reaction rate constants. The chiral polarization $\eta$ plays the role of an order parameter for chiral systems[31]: The value $|\eta| = 1$ corresponds to a totally ordered—i.e., chirally pure—state, while the value $\eta = 0$ corresponds to a racemic state. Studies of the behavior of chiral systems in terms of the variables $(x_L, x_D)$ and $(\eta, \theta)$ are completely equivalent, since the transformation $(x_L, x_D) \to (\eta, \theta)$ changes neither the numbers nor types of singular points of the system.

Depending on the nature of the chemical transforma-

TABLE II. Basic types of processes in chiral systems.

| Block | Reaction | Type of process | Dynamic equation for $\eta$ ($\eta = (x_L - x_D)/(x_L + x_D)$, $\theta = v(k_i)(x_L + x_D)$) | | $\eta_{max}$ ($t \to \infty$) | |
|---|---|---|---|---|---|---|
| | | | AF $= g = 0$ | AF $= g \neq 0$ | $g = 0$ | $g \neq 0$ |
| I | $A \xrightarrow{k^L} L$, $A \xrightarrow{k^D} D$, Synthesis | Racemizing | $\dot{\eta} = -\left(\frac{kA}{\theta}\right)\eta$ | $\dot{\eta} = \left(\frac{kA}{\theta}\right) \times (g - \eta)$ | 0 | $g$ |
| II | $L \underset{}{\overset{k_r}{\rightleftarrows}} D$, Racemization | » | $\dot{\eta} = -2k_r\eta$ | | 0 | 0 |
| III | $A + L \xrightarrow{k} L + D$, $A + D \xrightarrow{k} L + D$, "Accidental" autocatalysis | » | $\dot{\eta} = -2kA\eta$ | | 0 | |
| IV | $L + L \xrightarrow{k^L} L + D$, $D + D \xrightarrow{k^D} L + D$, Binary racemization | » | $\dot{\eta} = -k\theta\eta$ | | 0 | |
| V | $L + L \xrightarrow{k^L} A + B$, $D + D \xrightarrow{k^D} A + B$, Binary destruction | » | $\dot{\eta} = -k\theta(\eta - \eta^3)$ | $\dot{\eta} = -\frac{1}{2} \times k\theta(g - \eta) \times (1 - \eta^2)$ | 0 | $g$ |
| VI | $A + 2L \xrightarrow{k} 2L + D$, $A + 2D \xrightarrow{k} 2D + L$, "Accidental" superautocatalysis | » | $\dot{\eta} = -\frac{k}{2} \times A\theta(\eta + \eta^3) - kA\theta\eta$ | | 0 | |
| VII | $L \xrightarrow{k^L} A$, $D \xrightarrow{k^D} A$, Destruction | Neutral | $\dot{\eta} = 0$ | $\dot{\eta} = kg(1 - \eta^2)$ | $\eta_0$ | $\lvert 1 \rvert$ |
| VIII | $A + L \xrightarrow{k^L} 2L$, $A + D \xrightarrow{k^D} 2D$, Autocatalysis | » | $\dot{\eta} = 0$ | $\dot{\eta} = kAg(1 - \eta^2)$ | $\eta_0$ | $\lvert 1 \rvert$ |
| IX | $L + D \xrightarrow{k^L} L + L$, $L + D \xrightarrow{k^D} D + D$, Cross-inversion | » | $\dot{\eta} = 0$ | $\dot{\eta} = 2k\theta g(1 - \eta^2)$ | $\eta_0$ | $\lvert 1 \rvert$ |
| X | $L + D \xrightarrow{k} A + B$, "Annihilation" | Deracemizing | $\dot{\eta} = \frac{k}{2}\theta(\eta - \eta^3)$ | | $\lvert 1 \rvert$ | |
| XI | $A + 2L \xrightarrow{k^L} 3L$, $A + 2L \xrightarrow{k^D} 3D$ | » | $\dot{\eta} = \frac{k}{2} \times A\theta(\eta - \eta^3)$ | $\dot{\eta} = \frac{k}{2} \times A\theta(g + \eta) \times (1 - \eta^2)$ | $\lvert 1 \rvert$ | $\lvert 1 \rvert$ |

tions in the system, i.e., depending on the processes in the chiral subsystem and the interaction of the chiral and achiral subsystems, one can identify the basic types of dynamic processes in chiral systems. There are only three of them (Table II).

*a) Racemizing* ($r$). Included in this category are processes involving a relaxation of chiral order to a racemic state. It can be seen from Table II that this category includes, first, reactions which are of zeroth order in the chiral reactants and, second, the racemization process proper and processes which stem from the finite stereoselectivity of the interactions of chiral molecules (blocks I–VI in Table II). The general form of the dynamic equation for processes of the racemizing type can be written as follows:

$$\left(\frac{d\eta}{dt}\right)_r = -a\eta.$$

Figure 11 shows a typical plot of $\eta(t)$.

*b) Neutral* ($N$). Processes of this type do not alter the chiral order of a system, leaving the initial chiral polarization of the system unchanged:

$$\left(\frac{d\eta}{dt}\right)_N = 0.$$

It follows from Table II that the category of neutral processes includes the autocatalytic synthesis of mirror

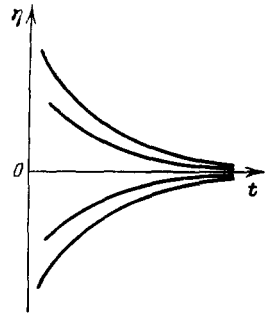


FIG. 11. The function $\eta(t)$ for a racemizing process.

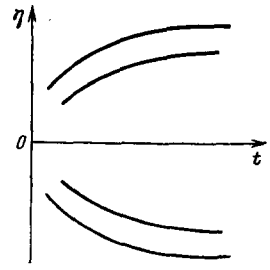


FIG. 13. The function $\eta(t)$ for a deracemizing process.

isomers (VIII), processes which destroy them (VII) (i.e., all irreversible reactions of first order in the concentrations of the antipodes), and the cross-inversion process (IX). Figure 12 shows the function $\eta(t)$ for neutral processes.

c) *Deracemizing* (*dr*). Processes of this type lead to an increase in the chiral order of a system (Fig. 13). A characteristic feature of processes of this type is a positive feedback in the chiral polarization, which arises because of the "interaction" of mirror isomers. As can be seen from Table II, this category includes the "annihilation" of antipodes in their interaction (L + D→A) (X) and "superautocatalysis" (A + L + L→3L, A + D + D→3D) (XI). The general form of the dynamic equation for chiral polarization in the case of deracemizing processes is

$$\left(\frac{d\eta}{dt}\right)_{dr} = \alpha(\theta)\eta - \beta(\theta)\eta^3. \tag{9}$$

The form of this equation is similar to that of equations in the theory of nonequilibrium phase transitions (Refs. 39 and 40, for example). This form of the equation is characteristic of systems which exhibit a critical behavior: At $\alpha/\beta < 0$, a racemic state is stable in the system. When the critical conditions ($\alpha/\beta = 0$) are reached, the racemic state loses its stability. At $\alpha/\beta > 0$, stable chirally polarized states arise; i.e., there is a spontaneous breaking of mirror symmetry.

We have some brief comments on Table II. This table gives "reaction building blocks" which can be used to construct fairly complex models for processes in an extremely simple way. It is easy to write dynamic equations which directly show the nature of the behavior of the chiral polarization in a model which has been constructed. On the other hand, this table can be used as a "stencil" for analyzing any proposed reaction model. This is the basic advantage of a classification based on the use of the variables $(\eta,\theta)$. Note that this classification makes it possible to identify a class of processes which are capable of effectively leading to the destruction of mirror symmetry—deracemizing processes—and specifies the minimum set of reactions i.e., building blocks which implement this process (Table III).

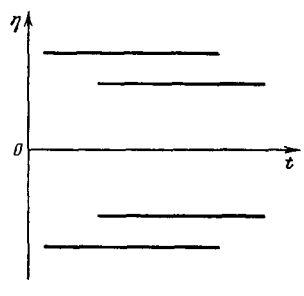


FIG. 12. The function $\eta(t)$ for a neutral process.

In order to distinguish among the basic types of processes—racemizing, neutral, and deracemizing—in chiral systems we have not considered possible effects of asymmetric factors—advantage factors—on these processes. The presence of an advantage factor has the consequence that the rate constants of mirror-image reactions (for L- and D-isomers) are no longer the same. A measure of an advantage factor can be introduced as the relative difference between the rate constants for mirror-image reactions:

$$g = \frac{k_i^{\mathrm{L}} - k_i^{\mathrm{D}}}{k_i^{\mathrm{L}} + k_i^{\mathrm{D}}}.$$

Incorporating an advantage factor leads to additional terms in the equations for chiral polarization. For processes of the racemizing type the contribution of an advantage factor is of the form

$$\left(\frac{d\eta}{dt}\right)_r^{(g)} = b_1 g,$$

while for neutral and deracemizing processes it is of the form

$$\left(\frac{d\eta}{dt}\right)_{N,dr}^{(g)} = b_2 g(1-\eta^2). \tag{10}$$

Since the equation for the chiral polarization for neutral processes is of the form $(d\eta/dt)_N = 0$ in the absence of an advantage factor, one would get the impression that a neutral process would become a deracemizing process in the presence of an advantage factor. This is not the case, however. In nonliving nature there are no processes with an absolute stereoselectivity. This circumstance means that the "wrong" reactions occur in parallel with the "right" ones. For example, the neutral process (VIII)

$$\mathrm{A} + \mathrm{L} \xrightarrow{k^{\mathrm{L}}} 2\mathrm{L},$$

$$\mathrm{A} + \mathrm{D} \xrightarrow{k^{\mathrm{D}}} 2\mathrm{D}$$

is actually always accompanied by a deracemizing process (III)

$$\mathrm{A} + \mathrm{L} \xrightarrow{k_{\mathrm{m}}} \mathrm{L} + \mathrm{D},$$

$$\mathrm{A} + \mathrm{D} \xrightarrow{k_{\mathrm{m}}} \mathrm{L} + \mathrm{D}.$$

A process of this sort makes a contribution $-2k_{\mathrm{m}}\eta$ to the equation for the chiral polarization. As a result we find the following equation for the chiral polarization:

TABLE III. Models for the development of chiral order.

| Type of model | Set of blocks | Set of reactions | Final state ($\eta_{max}$) | Ref. |
|---|---|---|---|---|
| Simple (evolutionary) | VIII (N) | $A+L \to 2L$, $A+D \to 2D$ ($k=k^L=k^D$), Jordan-Kuhn model | $\eta_\infty=\eta_0$ | 4,41, 42,89 |
| To " " | VII(N), $g$-CPL | $L \xrightarrow{k^L} A$, $D \xrightarrow{k^D} A$ | 1 | 47,48 |
| " " | I (r) | $A \xrightarrow{k^L} L$, $A \xrightarrow{k^D} D$, | $\frac{g}{k}$ | 103,112 |
| | VII (N) | $L \xrightarrow{k^L} A$, $D \xrightarrow{k^D} A$, | | |
| | II (r), $g$-WNC | $L \underset{}{\overset{k}{\rightleftarrows}} D$ | | |
| " " | VII (N) | $L \xrightarrow{k^L} A$, $D \xrightarrow{k^D} A$, | | |
| | II (r), $g$-$\beta$ radiolysis | $L \overset{k}{\rightleftarrows} D$ | $\frac{g}{k}$ | 111 |
| Bifurcation | VIII (N) | $A+L \xrightarrow{k} 2L$, $A+D \xrightarrow{k} 2D$ | $\lvert 1 \rvert$ | 148 |
| | X (dr) | $L+D \xrightarrow{k_a} B$, Frank model | | |
| " | I (r) | $A \xrightarrow{k^L} L$, $A \xrightarrow{k^D} D$ | 0 for $\rho<\rho_c$, | 151–156 |
| | VIII (N) | $A+L \rightleftarrows 2h$, $A+D \rightleftarrows 2D$ | $\pm\left(1-\frac{\rho_c}{\rho}\right)^{1/2}$ for $\rho>\rho_c$, | |
| | X (dr), $g$-WNC | $L+D \to B$, Modified Frank model | $\rho=f(k_i, x_A)$ | |
| " | VI (r) | $A+2L \to 3L$, $A+2D \to 3D$ | 0 for $\rho<\rho_c$, | 144 |
| | XI (dr) | $A+2L \to 2h+D$, $A+2D \to 2D+L$, "Supercompetition" model | $\pm\left(1-\frac{\rho_c}{\rho}\right)$ for $\rho>\rho_c$, $\rho=f(k_i, x_A)$ | |

The various sets of reactions, both with and without an advantage factor, were analyzed in detail in Refs. 38 and 125–127. CPL = Circularly polarized light; WNC = weak neutral currents.

$$\frac{d\eta}{d\tau}=g(1-\eta^2)-k_R\eta \qquad (11)$$

$$\left(\tau\equiv\frac{1}{2}(k^L+k^D)At,\quad k_R\equiv\frac{4k_m}{k^L+k^D}\right).$$

The chiral polarization of the system tends not toward 1, as would follow from (10), but toward a value $\sim g/k_R$. We will estimate this quantity in order of magnitude in §5 in a discussion of the hypothesis that the chiral purity of the organic medium arose from an effect of an advantage factor on the "primeval soup."

We wish to stress that an analysis of the dynamics of chiral systems in terms of the variables $(\eta,\theta)$ furnishes an unambiguous answer to the question of which types of processes occur in the system, in contrast with a similar study carried out in terms of other variables. We will demonstrate this point on the example of the rather popular hypothesis of an autocatalytic appearance of chiral purity, which has been suggested by several authors.[4,41,42] This hypothesis is based on the following reaction scheme:

$$A+L \xrightarrow{k} 2L,\quad A+D \xrightarrow{k} 2D$$

(the rate constants of the mirror-image reactions are the same—there is no advantage factor). The authors of this hypothesis started from the position that the dynamic equation for the difference between the antipodes, $\alpha=(x_L-x_D)/A$, is

$$\frac{d\alpha}{d\tau}=\alpha \qquad (\tau\equiv kAt).$$

Working from the solution of this equation,

$$\alpha(\tau)=\alpha(0)e^{\tau},$$

they concluded that since the difference between the antipodes (which arose as the result of some fluctuation at the initial time) increases exponentially, such a process could lead to the dominance of one of the antipodes in the biosphere. That conclusion, however, is erroneous. The equation for the sum of the antipodes, $\theta=(x_L+x_D)/A$,

$$\frac{d\theta}{d\tau}=\theta,$$

has the same form as the equation for the difference, so the sum of the antipodes also increases exponentially (with the same argument). The chiral order of the system, described by the value of the chiral polarization ($\eta=\alpha/\theta$), does not

change; it remains equal to its original value: $\eta(\tau) = \eta(0)$.

Another model of this type is the model which Norden[48] proposed for the development of the chiral purity of the biosphere, on the basis of Eigen's idea[43] of hypercycles. The equations of Eigen's model for two mirror isomers can be written in the form

$$\frac{dx_i}{dt} = (A_i Q_i - D_i)\, x_i - \varphi_0 x_i + \sum_{i \neq j} \varphi_{ij} x_j \qquad (i = \mathrm{L},\ \mathrm{D}),$$

where $A_i$ and $D_i$ are the rate constants of the autocatalytic synthesis and destruction of the isomers, $Q_i$ is the fraction of isomers which reproduce themselves "correctly," $\varphi_0$ is the rate constant for the escape of isomers from the reaction region, and $\varphi_{ij}$ is the rate constant of the "incorrect" synthesis, i.e., of the racemizing process. These equations can be rewritten in terms of $\eta$ and $\theta$:

$$\frac{d\eta}{d\tau} = g(1-\eta^2) - k_R \eta,$$

$$\frac{d\theta}{d\tau} = \left(1 - \frac{\varphi_0 - \varphi_{ij}}{\Sigma W}\right)\theta + g\theta\eta;$$

Here $g = (W^{\mathrm{L}} - W^{\mathrm{D}})/(W^{\mathrm{L}} + W^{\mathrm{D}})$ $W^i = A_i Q_i - D_i$, $i = \mathrm{L,D}$) is the advantage factor which stems from the "selective advantage"[43] of the L-isomer, and $K_R$ is the effective constant of the racemizing process $k_R = 2\varphi_{ij}/(W^{\mathrm{L}} + W^{\mathrm{D}})$. It is easy to see that this is a typical model of a neutral process under the influence of an advantage factor; it incorporates the presence of a racemizing process [see Eq.(11)]. Consequently, the maximum degree of chiral polarization which can be attained in such a system cannot exceed $g/k_R$, and for realistic values of $g$ and $k_R$ we would have $g/k_R < 1$.

In analyzing the processes which occur in chiral systems in order to determine whether they are capable of leading to a pronounced breaking of mirror symmetry we should be very cautious in drawing conclusions on the basis of equations for the concentration of mirror isomers (it is difficult to conclude from the form of these equations whether a given model is suitable in the problem of the development of chiral order in the course of evolution) and equations for the difference between antipodes, since they may lead to incorrect conclusions.

We turn now to a discussion of two alternative hypotheses for an abiogenic chiral purity.

## 5. THE ADVANTAGE-FACTOR HYPOTHESIS: THE SEQUENTIAL-EVOLUTION SCENARIO

This hypothesis is based on the idea that the rate constants of the reactions in which mirror-isomer molecules are involved may differ if there is some asymmetric influence. These differences would have played a decisive role in the breaking of mirror symmetry in a prebiological organic medium. This hypothesis can be described schematically as follows:

| | Advantage Factor | |
|---|---|---|
| Primeval racemic soup | Development and intensification of an external asymmetry in physicochemical transformations | Chiral purity of prebiosphere |

The idea that the dissymmetry of living matter is a consequence of physical factors of some sort or other dates back to Pasteur.[44] This idea arose at the very beginning of the problem of the development of the chiral purity of the biosphere, and it has dominated this problem down to the present since the idea that physicochemical processes would be incapable of breaking mirror symmetry in the absence of an advantage factor has dominated the thinking of researchers (§3).

The literature presents a great diversity of assumptions regarding the nature of the advantage factor which was responsible for the breaking of mirror symmetry in the course of the process by which life originated (see, for example, the bibliography in Ref. 45). All the physical sources of a nonequivalence of the *levo* and *dextro* isomers which have been proposed can be put in one of two categories.

First, there are the local advantage factors. Examples are circularly polarized light,[46–49] various combinations of static electric and magnetic fields,[50–52] "mechanical" advantage factors (e.g., a combination of the gravitational field and the forces which arise during rotation), the Coriolis forces,[53–55] and "mixed" advantage factors, i.e., combinations of mechanical forces and electromagnetic fields.[51] We could also include in this category the effect of lightning[54] and a combination of a magnetic field and linearly polarized light.[56,57] Some more-exotic candidates have also been advanced, e.g., circularly polarized electromagnetic radiation generated by solar flares.[58] The expression "local advantage factors" is used to emphasize that the advantage factors of this type may or may not exist in some particular spatial region (on the earth's surface) and that they vary from region to region or act for only a limited time.

The second category is that of global advantage factors. This category includes the sources of an advantage factor which stem from parity nonconservation in the weak interactions of elementary particles. Such advantage factors may be manifested either in the course of radiolysis under the influence of polarized products of $\beta$-decay (the Vester-Ulbricht hypothesis[59,60]) or in an effect of weak neutral currents.[61,62]

How would a difference between the rate constants for chemical processes be caused by an advantage factor?

There are two mechanisms by which an advantage factor could operate. One involves the lifting of an energy degeneracy of molecules which are mirror isomers (§3, Fig. 14). In this case, the internal energies of the antipodes become different ($E_{\mathrm{L}} \neq E_{\mathrm{D}}$), and as a result of this difference the reactivities of these isomers are slightly different. This

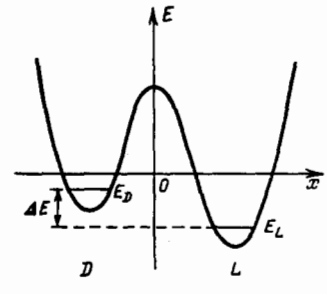


FIG. 14. Chiral potential with parity nonconservation. Here $\Delta E$ is the splitting of the levels of the L- and D-states of the molecules.

mechanism leads to an internal difference between the isomer molecules. It operates in the case of an advantage factor caused by weak neutral currents. If we denote by $\hat{H}_{\rm WNC}$ the Hamiltonian which is responsible for weak neutral currents, the energy difference between the isomers, $\Delta E_{\rm WNC}$, is given by

$$\Delta E_{\rm WNC} = \langle {\rm L}|\hat{H}_{\rm WNC}|{\rm L}\rangle - \langle {\rm D}|\hat{\sigma}^{-1}\hat{H}_{\rm WNC}\hat{\sigma}|{\rm D}\rangle, \qquad (12)$$

where $\hat{\sigma}$ is the inversion operator.

In the second mechanism, a difference in the reactivities of antipodal molecules arises from the circumstance that their interactions with a chiral advantage factor are not the same (e.g., an interaction with circularly polarized light or polarized $\beta$-decay radiation). Under the influence of an advantage factor of a certain chirality (e.g., left-hand or right-hand circularly polarized light), the isomers with one type of chirality are excited more efficiently than are the isomers of the opposite chirality, so it is easier for them to undergo chemical transformations, although their internal energy remains the same in the unexcited state. The difference in the activation energies of the isomers is given by

$$\Delta E_{\beta} = \langle {\rm L}|\hat{H}_{\rm int}|{\rm L}\rangle - \langle {\rm D}|\hat{H}_{\rm int}|{\rm D}\rangle,$$

where $\hat{H}_{\rm int}$ is the Hamiltonian of the interaction of an isomer molecule with the advantage factor. If we take the relative difference between the rate constants of the mirror-image reactions,

$$g = (k_i^{\rm L} - k_i^{\rm D})(k_i^{\rm L} + k_i^{\rm D})^{-1}, \qquad (13)$$

as a measure of the advantage factor, and if we use an Arrhenius dependence of the reaction rate constant on the activation energy,

$$k^{\rm L} = A\exp\left(-\frac{E_{\rm L}}{k_{\rm B}T}\right), \quad k^{\rm D} = A\exp\left(-\frac{E_{\rm D}}{k_{\rm B}T}\right),$$

$$E_{\rm L} = E_{\rm D} \pm \Delta E,$$

we find the following expression for our measure of the advantage factor:

$$g = \frac{\exp(-E_{\rm L}/k_{\rm B}T) - \exp(-E_{\rm D}/k_{\rm B}T)}{\exp(-F_{\rm L}/k_{\rm B}T) + \exp(-E_{\rm D}/k_{\rm B}T)} \approx \frac{\Delta E}{k_{\rm B}T}. \qquad (14)$$

Formally, the measure of the advantage factor has been defined in the same way for the two mechanisms, but we wish to stress that the quantity $\Delta E$ has different meanings in the two cases.

The question of the maximum attainable degree of asymmetry in some scenario plays a very important role in an analysis of the scenario for the breaking of mirror symmetry. The reason is the need for chiral purity of the medium as a necessary step preceding the formation of self-replicating systems.

In the scenario of sequential and continuous evolution, it is customary to take basic processes to be such processes as the destruction of isomers (VII),

$$\mathrm{L} \xrightarrow{k_{\rm d}^{\rm L}} \mathrm{A}, \quad \mathrm{D} \xrightarrow{k_{\rm d}^{\rm D}} \mathrm{A}; \qquad (15)$$

simple synthesis (I),

$$\mathrm{A} \xrightarrow{k_{\rm c}^{\rm L}} \mathrm{L}, \quad \mathrm{A} \xrightarrow{k_{\rm c}^{\rm D}} \mathrm{D}; \qquad (16)$$

or the autocatalytic synthesis (VIII)

$$\mathrm{A} + \mathrm{L} \xrightarrow{k_{\rm a}^{\rm L}} 2\mathrm{L}, \quad \mathrm{A} + \mathrm{D} \xrightarrow{k_{\rm a}^{\rm D}} 2\mathrm{D}, \qquad (17)$$

of isomers from an achiral substrate in the presence of an advantage factor ($k_i^{\rm L}$ and $k_i^{\rm D}$ are the rate constants of the corresponding reactions). According to the classification of §4, reactions (15) and (17) are neutral processes, while reaction (16) is a racemizing process. In an abiogenic scenario for the breaking of mirror symmetry, we would have to supplement reactions (15) and (17) with a consideration of the corresponding racemizing processes. For reaction (15), this is the induced racemization

$$\mathrm{L} \underset{}{\overset{k_{\rm r}}{\rightleftarrows}} \mathrm{D}, \qquad (18)$$

while for reaction (17) it is either induced racemization (18) or the "incorrect" synthesis reaction, which is manifested as a result of a nonabsolute stereoselectivity of the chemical reactions,

$$\mathrm{A} + \mathrm{L} \xrightarrow{k_{\rm m}} \mathrm{L} + \mathrm{D}, \quad \mathrm{A} + \mathrm{D} \xrightarrow{k_{\rm m}} \mathrm{L} + \mathrm{D}. \qquad (19)$$

For simple-synthesis reaction (16), even if we ignore additional racemizing processes, we find the following value for the maximum attainable asymmetry of the system (Table II):

$$\eta_{\max} = g.$$

Taking racemizing processes (18) and (19) into account, we find the maximum attainable asymmetry of the system for reactions (15) and (17) to be [see Table III and Eq.(11)]

$$\eta_{\max} = \frac{g}{k_{\rm R}}\left\{1 + \left[1 + \left(\frac{g}{k_{\rm R}}\right)^2\right]^{1/2}\right\}^{-1} \approx \frac{g}{k_{\rm R}}, \qquad (20)$$

where $k_{\rm R}$ is the dimensionless effective rate constant of a racemizing process.

In summary, in the "evolutionary" scenario the value of $\eta_{\max}$ is determined either directly by $g$ or by the ratio $g/k_{\rm R}$.

### 5.1. "Selection rules" for the advantage factor

We mentioned above that a large variety of asymmetry sources have been proposed. Actually, not all of them are suited for the role of advantage factor. A physical source of an advantage factor must satisfy certain symmetry requirements.

We recall that the property of chirality is described most simply by a pseudoscalar $\chi$ whose value changes sign when we transform from a right-handed coordinate system to a left-handed one, i.e., under mirror reflection:

$$\hat{\sigma}\chi = -\chi,$$

where $\hat{\sigma}$ is the inversion operator. A quantity of this sort can be constructed as the scalar product of an axial vector ($\mathbf{A}$) and a polar vector ($\mathbf{P}$) which are associated with the chiral object:

$$\chi = (\mathbf{AP}).$$

We know quite well that (natural) optical activity is observed for only those chiral molecules which belong to point groups which do not contain mirror-rotation elements (and

for which both electric dipole and magnetic dipole transitions are allowed):

$$\langle i|\mathbf{d}|j\rangle\langle j|\mathbf{m}|i\rangle \neq 0;$$

here the operators **d** and **m** represent respectively the electric and magnetic moments of the transition $i \to j$.

It would thus seem that any combination of a polar field and an axial field could in principle be thought of as a possible source of an advantage factor. Actually, the requirements imposed on the source of an advantage factor are even more severe. Analysis[63–72] shows that a combination of static fields, one described by an axial vector and another by a polar vector (e.g., **E** and **B** or a gravitational field and a centrifugal force), is not a "true" advantage factor (at least for equilibrium processes) in the sense that the influence of such an advantage factor on chemical transformations in a chiral system does not lead to an asymmetry, i.e., an inequality of the concentrations of L- and D-isomers. To demonstrate this point, we consider a simple example (following Ref. 67).

We assume that we have a chemical system in which achiral molecules are transformed into L- and D-isomer molecules in the presence of an advantage factor, the source of which is a combination of a polar field **P** and an axial field **A**, both of which are static: $L \rightleftarrows B \leftrightarrows D$. We denote the state of the molecules in the presence of the advantage factor by $(M, \mathbf{P}, \mathbf{A})$, where $M = L,D$. We introduce two symmetry operations: time reversal ($T$) and mirror reflection ($\hat{\sigma}$). Since we have

$$\hat{\sigma}\mathbf{P} = \mathbf{P}, \quad \hat{\sigma}\mathbf{A} = -\hat{\mathbf{A}}$$

and

$$\hat{T}\mathbf{P} = \mathbf{P}, \quad \hat{T}\mathbf{A} = -\mathbf{A},$$

we can write

$$(\mathrm{L}, \mathbf{P}, \mathbf{A}) \xrightarrow{\hat{\sigma}} (D, \mathbf{P}, -\mathbf{A}) \xrightarrow{\hat{T}} (\mathrm{D}, \mathbf{P}, \mathbf{A}). \qquad (21)$$

Equation (21) states that the L-isomers have the same energy as the D-isomers. Since the partition functions of the isomer molecules are identical, it follows from (21) that their equilibrium concentrations are equal even in the presence of the advantage factor:

$$x_{\mathrm{L}} = x_{\mathrm{D}}.$$

A "true" advantage factor (in the terminology proposed by Barron) is an asymmetric agent which has the property of "helicity"; i.e., it would be one of those physical fields, types of radiation, etc., which can exist in two enantiomer forms which transform into their antipodes under space inversion but which do not change under time reversal combined with any spatial rotation.[68–72] Among the advantage factors listed above, those which fall in this category are the following: circularly polarized light, a combination of a magnetic field with linearly polarized light, polarized $\beta$-decay products, and weak neutral currents (Table IV).

### 5.2. Local advantage factors

*5.2.1. Circularly polarized light.* An asymmetry in the reaction products during the photolysis of a racemate by circularly polarized light was observed experimentally nearly 60 yr ago,[73] and this method of asymmetric synthesis is still part of laboratory practice (Ref. 74, for example). The sunlight which is circularly polarized at twilight at the surface in the IR part of the spectrum (800 nm) constitutes 0.1% of the total flux.[75] In the UV region, however, which is the best for causing reactions in photochemical processes, one does not observe a circular polarization sufficient for asymmetric photolysis; i.e., this polarization amounts to less than 0.01%. We should also stress that the circular polarization of sunlight is a consequence of parity-conserving electromagnetic interactions in the earth's atmosphere, so circularly polarized light could be only a local advantage factor. On the average over the entire earth's surface, and in view of the rotation of the earth, the effect of circularly polarized light should disappear.

*5.2.2. Magnetic and gravitational fields, etc.* Since such sources as magnetic and gravitational fields, the centrifugal

TABLE IV. Physical advantage factors.

| Type of advantage factor | "True" (+) or "imaginary" (−) | $g$ |
|---|---|---|
| Circularly polarized light | + | $10^{-2} \div 10^{-4}$ |
| Static magnetic field (SMF) (**B**) | − | |
| Static electric field (SEF) (**E**) | − | |
| Gravitational field (GF) (**G**) SMF + SEF | − | $\chi_i$ (**EB**) |
| | − | |
| Rotation (Coriolis forces) + GF | − | $\chi_j$ ([$\omega$**v**] **G**) − $\chi_j$ ($\Omega$**G**) |
| SMF + GF | − | $\chi_m$ (**BG**) |
| Rotation + SMF + SEF | + | $\chi_n$( $\omega$ [**EB**]) |
| Rotation + SMF + GF | + | $\chi_p$ (**B** [$\omega$**G**]) |
| SMF + linearly polarized light | + | $\chi_r$ (**BK**) |
| Weak neutral currents | + | $\chi_q z^5 10^{-20} \frac{1}{k_B T} \sim 10^{-17}$ |
| Longitudinally polarized $\beta$ particles | + | $h_e \frac{\sigma^{\mathrm{L}} - \sigma^{\mathrm{D}}}{\sigma^{\mathrm{L}} + \sigma^{\mathrm{D}}} \sim 10^{-11}$ |

*Notation*: $\chi$—Factor determined by molecular structure; $h_e$—helicity of $\beta$ particles $\langle \hat{s}\hat{p} \rangle$, where the operators $\hat{s}$ and $\hat{p}$ represent the spin and momentum of the $\beta$ particle; $\sigma^{\mathrm{L,D}}$—cross sections for the interaction of polarized $\beta$ particles with molecules; $z$—atomic number.

forces which arise in vortices, etc., do not satisfy even the simplest necessary condition which sources of an advantage factor must meet (a pseudoscalar can not be associated with them), they cannot be regarded as advantage factors.

*5.2.3. Combinations of static axial and polar fields.* According to Subsection 5.1, an asymmetry could not be generated by advantage factors of this sort in chemical reactions which occur under equilibrium conditions.

Furthermore, the recent hypothesis of an advantage factor stemming from the interaction of the geomagnetic field with a magnetic moment induced in molecules by the motion of the ions of the medium [76-78] also runs into the difficulties mentioned above: Analysis shows that an advantage factor of this sort is not a true advantage factor in Barron's classification.

Accordingly, reports of an asymmetry of reaction products obtained in experiments with advantage factors of this sort (e.g., an asymmetric synthesis reaction in collinear electric and magnetic fields[50] and synthesis in a rotating vessel[51,53,55]) should be received with much caution. In the careful experiments of Ref. 54, where a study was made of the possibility of asymmetric transformations in a rotating vessel, no asymmetry was found in the reaction products.

There is reason to believe that the conclusions reached in a study of equilibrium processes under the influence of such advantage factors also apply to processes which occur under nonequilibrium conditions,[67] although the opposite point of view has been expressed.[70,71] This question requires further study.[72]

Let us nevertheless assume that an advantage factor of this type is a "true" advantage factor for nonequilibrium processes. Mead and Moskowitz worked from the experimental conditions on asymmetric synthesis in a rotating vessel[53] to estimate the magnitude of the effect. They showed that in this case it was $g < 10^{-17}$. If we note that the reaction vessel was rotating at a velocity $\sim 1.4 \cdot 10^4$ rpm, which is of course far higher than the rotation velocity in atmospheric vortices or in the rotation of gas jets during the eruptions of volcanos, we find a figure $g \ll 10^{-17}$ for natural conditions. We thus have $\eta_{\max} = g \ll 10^{-17}$. An advantage factor of such an amplitude obviously could not play any role in breaking the mirror symmetry of the primeval soup.

In completing this brief review of the hypothesis of local advantage factors, we would like to call the reader's attention to some fundamental difficulties here. First, the greatest asymmetry which is achievable (even in experiments) is no greater than $\sim 10^2$ (these would be experiments on photolysis in a beam of circularly polarized light). In light of the results presented in §2, this figure is obviously far from adequate from the standpoint of the problem of the origin of chiral purity. Second, no actual local advantage factor whose distribution on the earth would have an asymmetry for the planet as a whole has yet to be proposed. We might add that one of the "oldest" and most popular sources of an advantage factor—enantiomorphic quartz crystals, on which a stereoselective sorption of isomer molecules could occur—is represented on the earth by a racemic mixture, according to detailed studies of the abundance of such crystals[77,78]—despite numerous assertions that the abundance of L-quartz is 0.1% greater than that of its D-antipode. This fact is a serious argument against the Cairns-Smith hypothesis,[79] presently popular, that clays and minerals played a key role in the origin of self-replicating systems.

In summary, processes which occur under the influence of local advantage factors on the earth could lead to the formation on our planet of only a racemic mixture of mirror isomers, at least in the evolutionary scenario for the arising of chiral purity.

### 5.3. Global advantage factors

The discovery of parity nonconservation in the weak interactions of elementary particles[80,81] has provided a physical basis for the suggestion that the asymmetry of the biosphere is a consequence of parity nonconservation in weak interactions.

Two mechanisms for a possible influence of parity nonconservation are being discussed in the literature. One is related to the so-called neutral currents. As far back as 1925, Le Bell[82] made the daring, but at the time purely speculative, suggestion that atoms have an internal chirality. A physical foundation for this suggestion was observed considerably later and was linked with a role played by weak interactions in the interaction of atomic-shell electrons with the nucleons of a nucleus: the existence of neutral currents.[83] Parity violation was linked with a vector neutral boson $z_0$ (Ref. 84). Because of neutral currents, the electronic structure of an atom may have an insignificant internal chirality. (An experimental study of optical activity due to neutral currents is presently being carried out in the vapor of heavy metals.[85-88]) As a result, as we have already mentioned, the *dextro* and *levo* molecules—mirror isomers—would differ only extremely insignificantly in terms of energy (we will offer some theoretical estimates of the possible energy nonequivalence of antipodal molecules below). Correspondingly, the rate constants for chemical reactions (synthesis, destruction, polymerization, etc.) in which enantiomers participate could be different, although to a very slight extent. The experimental observation of such differences apparently lies beyond the reach of today's capabilities, but many authors have suggested that the physicochemical processes which presumably underlie chemical evolution have the capability of building up and intensifying such insignificant differences. In principle, this mechanism could result in a macroscopic excess of one of the isomer forms of an organic substance (see Refs. 61 and 89–91, for example).

Another possible mechanism is related to an effect of radioactive emission on the chemical transformation (synthesis or destruction) of mirror isomers. As we know, parity nonconservation during $\beta$ decay leads to the predominant appearance of longitudinally polarized electrons (or positrons). As such electrons (or positrons) interact directly with chiral molecules, or as they generate in a substance bremsstrahlung with a circularly polarized component which interacts selectively with the antipodes, they may give rise to an excess of one of the antipodes in the course of physicochemical transformations in a chemical system.

*5.3.1. Weak neutral currents.* Weak neutral currents perturb stationary states of atoms and molecules, "lifting" the energy degeneracy for antipodal states of a chiral molecule. Specifically, we have

$$\langle L|\hat{H}_{WNC}|L\rangle = -\langle D|\hat{\sigma}^{-1}\hat{H}_{WNC}\hat{\sigma}|D\rangle,$$

and the energy levels of the two antipodes differ by an

amount

$$\Delta E_{\mathrm{WNC}} = 2\langle \mathrm{L}|\hat{H}_{\mathrm{WNC}}|\mathrm{L}\rangle$$

as a result of weak neutral currents ($\hat{H}_{\mathrm{WNC}}$ is the potential describing the contribution of the weak neutral currents, and $\sigma$ is the operator of space inversion).

Using the model of an atom in a chiral potential, we can find an order-of-magnitude estimate of $\Delta E_{\mathrm{WNC}}$ (Refs. 92–95):

$$\Delta E_{\mathrm{WNC}} \approx qZ^5 \cdot 10^{-20} \text{ a.u.} = qZ^5 \cdot 10^{-14} \text{ J/mole},$$

where $Z$ is the atomic number, and $q$ is a structural asymmetry factor. The potential $H$ can be written as the sum of three binary-interaction potentials[93–95]:

$$\hat{H}_{\mathrm{WNC}} = \hat{H}^{\mathrm{ee}}_{\mathrm{WNC}} + \hat{H}^{\mathrm{pe}}_{\mathrm{WNC}} + \hat{H}^{\mathrm{ne}}_{\mathrm{WNC}},$$

where $\hat{H}^{\mathrm{ee}}_{\mathrm{WNC}}$ is the electron-electron potential, $\hat{H}^{\mathrm{pe}}_{\mathrm{WNC}}$ the proton-electron potential, and $\hat{H}^{\mathrm{ne}}_{\mathrm{WNC}}$ the neutron-electron potential. The potential $\hat{H}^{\mathrm{ne}}_{\mathrm{WNC}}$ describes a predominant contribution to the splitting $\Delta E_{\mathrm{WNC}}$ of the energy of chiral antipodal molecules due to weak neutral currents. The two other potentials, $\hat{H}^{\mathrm{ee}}_{\mathrm{WNC}}$ and $\hat{H}^{\mathrm{pe}}_{\mathrm{WNC}}$, depend on $(1 - 4\sin^2\theta_{\mathrm{W}})$, i.e., on the Weinberg angle. The experimental values of $\sin^2\theta_{\mathrm{W}}$ lie in the interval[99,100] (0.215–0.23, so $\hat{H}^{\mathrm{ee}}_{\mathrm{WNC}}$ and $\hat{H}^{\mathrm{pe}}_{\mathrm{WNC}}$ do indeed make a contribution much smaller than that of $\hat{H}^{\mathrm{ne}}_{\mathrm{WNC}}$. The reader interested in the details of the calculation of $\Delta E_{\mathrm{WNC}}$ might look in Refs. 92–98.

In a series of papers, Mason and Tranter[93–98,101,102] calculated the values of $\Delta E_{\mathrm{WNC}}$ caused by weak neutral currents for several organic compounds, including some amino acids (alanine, valine, serine),[93–95] peptides,[93–98] and tetrahydrofurans[101,102] (the latter are possibly predecessors of sugars). Mason and Tranter succeeded in demonstrating that weak neutral currents shift the energy levels of antipodes, so that the L-isomers of the amino acids have an energy lower than that of the D-isomers. A corresponding result was derived for the predecessors of sugars: The D-isomers have an energy advantage over the L-isomers. This result means that the sign of the chirality of the biosphere and the sign of the chirality of the advantage factor due to the weak neutral currents are the same. The energy difference between the antipodes (for both the amino acids and the tetrahydrofurans) is of the order of $10^{-20}$ a.u. ($10^{-14}$ J/mole), and a measure of this advantage factor is the quantity

$$g \approx \frac{\Delta E_{\mathrm{WNC}}}{k_{\mathrm{B}}T} \approx 10^{-17} \tag{22}$$

($T = 300$ K).

The advantage factor due to weak neutral currents is thus extremely small. Until recently, however, the hypothesis that even such a weak advantage factor as that stemming from weak neutral currents could lead to the dominance of one of the isomer forms in the synthesis of polymers was extremely popular. This hypothesis, which was originally advanced by the Japanese chemist Yamagata,[89] can be summarized as follows: We assume that *levo* (L) and *dextro* (D) polymers of length $n$ are formed in a chemical system in accordance with the scheme

$$\mathrm{L} \xrightarrow{p_{\mathrm{L}}} \mathrm{L}+\mathrm{L} \xrightarrow{p_{\mathrm{L}}} \ldots \xrightarrow{p_{\mathrm{L}}} n\mathrm{L}, \quad \mathrm{D} \xrightarrow{p_{\mathrm{D}}} \mathrm{D}+\mathrm{D} \xrightarrow{p_{\mathrm{D}}} \ldots \xrightarrow{p_{\mathrm{D}}} n\mathrm{D}. \tag{23}$$

In the presence of an advantage factor, the probabilities $p_{\mathrm{L}}$ and $p_{\mathrm{D}}$ are slightly different:

$$p_{\mathrm{L}} = p(1+g), \quad p_{\mathrm{D}} = p(1-g).$$

By solving the kinetic equations corresponding to scheme (23), one finds the following ratio of the numbers of *levo* and *dextro* polymers of length $n$:

$$\frac{N^{(n)}_{\mathrm{L}}}{N^{(n)}_{\mathrm{D}}} = e^{gn}.$$

It is easy to see, however, that even for very large molecules ($n = 10^6$), with a realistic value $g \sim 10^{-17}$, the chiral polarization in such a system would not exceed

$$\eta_{\max} = \frac{1-\exp(gn)}{1+\exp(gn)} \approx gn \sim 10^{-11} \tag{24}$$

(it was previously assumed that parity nonconservation in weak interactions could lead to values $g \gg 10^{-7}$). Furthermore, as was shown in Ref. 103, incorporating the inverse reactions in scheme (23)—these inverse reactions always occur along with the forward reactions—and incorporating the finite stereoselectivity lead to

$$\frac{N^{(n)}_{\mathrm{L}}}{N^{(n)}_{\mathrm{D}}} = 1;$$

i.e., the medium remains racemic.

We can also evaluate $\eta_{\max}$ in another way. Let us assume that the rate constant (the probability $p$) for the incorporation of an isomer of the foreign chirality in a chain which is being synthesized does not exceed $10^{-6}$–$10^{-8}$ (this estimate is on the low side for chemical processes characteristic of biochemical reactions and modern organisms). From (24) we then find

$$\eta_{\max} \approx \frac{g}{p} = 10^{-11} - 10^{-9}.$$

We thus see that the problem of the development of the chiral purity of the biosphere as a result of an advantage factor stemming from weak neutral currents has not been solved on the basis of "simple" evolutionary hypotheses.

*5.3.2. $\beta$ decay.* Currently the most popular mechanism for the effect of the products of $\beta$ decay on chiral molecules is the asymmetric radiolysis of these molecules due to longitudinally polarized electrons and positrons (Refs. 104–106, for example). The case of greatest interest is the radiolysis accompanying the decay of such nuclei as $^{14}$C, $^{40}$K, $^{235}$U, and $^{26}$Al, which are quite abundant in the earth's crust, the ocean, and the biosphere.

The asymmetry of the radiolysis of antipodal molecules as they interact with longitudinally polarized $\beta$ radiation can be written in the following form[107,108]:

$$A_{\mathrm{R}} = |h(\mathrm{e}^{\pm})|H_{\mathrm{R}}(E, Z); \tag{25}$$

here $h(\mathrm{e}^{\pm}) = \langle \hat{s}_i \hat{p}_i \rangle$—the helicity of electron (or positron) $i$—is the degree of correlation between the spin of the particle, $\hat{s}_i$ and its momentum $p_i$, $Z$ is the atomic member of the nucleus, and

$$H_{\mathrm{R}} = \frac{\sigma^{+}(\mathrm{L}) - \sigma^{-}(\mathrm{L})}{\sigma^{+}(\mathrm{L}) + \sigma^{-}(\mathrm{L})} = \frac{\sigma^{\pm}(\mathrm{L}) - \sigma^{\pm}(\mathrm{D})}{\sigma^{\pm}(\mathrm{L}) + \sigma^{\pm}(\mathrm{D})} \tag{26}$$

is the asymmetry of the interaction of longitudinally polarized $\beta$ particles with L- and D-isomers [$\sigma^{\pm}$ is the cross

section for the interaction of the molecules with the particles of positive (negative) helicity]. In the energy range $100 < E < 500$ keV, the asymmetry $H_R$ can be written as follows[109] (in the nonrelativistic Born approximation):

$$H_R \approx \frac{q_R (\alpha Z)^2}{2E \ln E}, \tag{27}$$

where $q_R$ is the molecular dissymmetry factor in the radiolysis of the molecules (this factor depends on the structure of the specific molecules). For $E = 100$ keV (a typical value of the electron energy in $\beta$ decay), expression (27) reduces to

$$H_R = 10^{-5} q (\alpha Z)^2. \tag{28}$$

Taking $q_R \sim 10^{-2}$–$10^{-3}$ (the amplitude of the circular dichroism in the absorption bands of amino acids), we find the following result for the asymmetry $H_R$ of the radiolysis of amino acids ($Z = 6$):

$$H_R = 10^{-10} - 10^{-11}. \tag{29}$$

Consequently, even in the case of a 100% polarization of the $\beta$ particles we would have

$$10^{-11} < A_R < 10^{-10}. \tag{30}$$

Actually, the values are $h(e^{\pm}) = f(E) \ll 1$ and $A_R < 10^{-11}$. Note also that $h(e)$ increases with increasing $E$, while the reactivity of the $\beta$ particles falls off, so the asymmetry of the reaction products would be reduced even further.

Zel'dovich and Saakyan[110] have derived corresponding results for the asymmetry of the radiolysis of chiral molecules by relativistic $\beta$ particles:

$$H_R \approx \alpha^2 \frac{v}{c} \frac{\mathrm{Im}\,(\mathbf{dm})}{|\mathbf{d}|^2}, \tag{31}$$

where **d** and **m** are the electric and magnetic dipole moments of the transition of the molecule from one state to the other in the course of the radiolysis reaction, and $v$ is the velocity of the electron. Transitions in intense absorption bands, which dominate the reaction cross section, lead to the following estimate:

$$\frac{(\mathbf{dm})}{|\mathbf{d}|^2} \sim 10^{-6}.$$

In this case, for electrons with $E = 100$ keV, we again find

$$H_R = 10^{-11}.$$

It is easy to see that $A_R$ is essentially equal to $g$; i.e., for radiolysis caused by longitudinally polarized particles from $\beta$ decay, the amplitude of the advantage factor is estimated to be

$$g \approx A_R \lesssim 10^{-10} \div 10^{-11}. \tag{32}$$

An asymmetric radiolysis of antipodes is described by the reaction scheme

$$\mathrm{L} \xrightarrow{k_d^L} \mathrm{A}, \quad \mathrm{D} \xrightarrow{k_d^D} \mathrm{A}. \tag{33}$$

In the process, however, an effective radioracemization also occurs:

$$\mathrm{L} \underset{\longleftarrow}{\overset{k_r}{\longrightarrow}} \mathrm{D}.$$

According to Table III and Eq. (20), the maximum chiral polarization attainable in a process of this sort depends on the ratio of the measure of the advantage factor, $g$, to the effective rate constant of the racemizing process, $k_R = 2k_r/(k_d^L + k_d^D)$, in the following way:

$$\eta_{max} = \frac{g}{k_R} \left\{ 1 + \left[ 1 + \left( \frac{g}{k_R} \right)^2 \right]^{1/2} \right\}^{-1}. \tag{34}$$

It is a simple matter to estimate $k_R$ for radiolysis. The radiolysis rate constant $k_d$ varies, for various amino acids, from $5 \cdot 10^{-9}$ s$^{-1}$ (in the case of the $\beta$ decay of $^{40}$K and $^{14}$C) to $5 \cdot 10^{-10}$ s$^{-1}$ for a "natural" nuclear reactor (such as Oklo).[111] The radioracemization rate constant is $k_r \sim 10^{-14}$–$10^{-12}$ s$^{-1}$ (Ref. 112). We thus find $k_R \sim 10^{-5}$–$10^{-2}$. From (34) we thus find the following estimate:

$$r_{max} = \frac{g}{k_R} \sim 10^{-9} \div 10^{-11}. \tag{35}$$

More-detailed calculations based on Eq. (34)] incorporating the temperature dependence of the reaction rate constants are reported in Ref. 111; the results are shown in Fig. 15 of the present paper.

Estimate (35) leads to the conclusion that the advantage factor which stems from parity nonconservation in $\beta$ decay could not be a source of a pronounced breaking of mirror symmetry in the course of the prebiological evolution in the evolutionary scenario.

On the basis of the results presented in this section of the review we can conclude that those sensational results on the $\beta$ radiolysis of racemates which are reported from time to time in the scientific literature (e.g., Refs. 113–116) are also artifacts and have subsequently either been acknowledged as erroneous by the authors themselves (e.g., Ref. 117) or been convincingly refuted (e.g., Refs. 118–120).

In summarizing this discussion of the hypothesis that an advantage factor influenced the breaking of mirror symmetry during the evolution of the original organic medium, we can confidently conclude that this hypothesis runs into difficulties which are so fundamental in nature that there is extremely serious doubt that this hypothesis would be capable of serving as the main scenario for the development of the chiral purity of the biosphere. It is totally obvious that the racemizing and neutral processes which are discussed within the framework of this hypothesis are incapable, even in the presence of an advantage factor, of destroying an initially

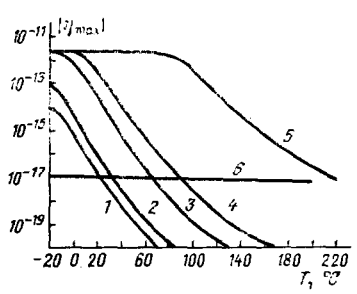


FIG. 15. Dependence of $|\eta_{max}|$ on $T$ for the radiolysis of alanine in an aqueous solution by natural sources of $\beta$ radiation.[111] 1—$^{40}$K, $^{14}$C in oceans; 2—average $\beta$ radioactivity of the earth's crust; 3—uranium deposits; 4—$^{26}$Al; 5—"natural" uranium reactor ($^{235}$U) (such as Oklo); 6—weak neutral currents (WNC).

racemic state of the organic medium. The theoretical analysis and the experimental data available today only support this conclusion.

On the other hand, experimental data which had accumulated by the mid-1970s provided evidence of an instability of the racemic state in a stereoselective, cooperative interaction of molecules which are mirror isomers even in relatively inviscid liquids. At the same time, a new direction in research on nonequilibrium processes and self-organization phenomena opened up: synergetics. It was in this direction that a step was taken toward new concepts in the problem of the breaking of mirror symmetry in the course of a prebiological evolution on the earth. We wish to stress that the studies by Morozov,[124-126] who formulated the concept of a spontaneous breaking of the mirror symmetry of organic matter in the course of evolution, played an extremely important role in the development of this direction.

## 6. SPONTANEOUS BREAKING OF MIRROR SYMMETRY: THE "CHIRAL CATASTROPHE" SCENARIO

No matter how attractive we may find the idea of explaining the "leftism" of the bioorganic world in terms of a breaking of the symmetry between left and right in the world of elementary particles, the results presented in the preceding section of this paper rule out such a "translation" of asymmetry, at least within the evolutionary scenario, i.e., in the case of a continuous and progressive buildup of an advantage factor during the process by which life originated.

An alternative to the scenario of a gradual buildup of an advantage factor is a spontaneous breaking of mirror symmetry in a prebiological organic medium—a self-organization of optical isomers in the course of chemical evolution.

From this point of view, the breaking of mirror symmetry and the formation of chirally pure forms of organic material were a consequence of the development and amplification in the course of the prebiological evolution of fluctuations which were of such a nature that they corresponded to an initially very slight predominance of one of the enantiomers. This thought was first expressed by Pearson[121] in a discussion of Japp's well-known paper on stereochemistry and vitalism.[122] Pearson suggested that in the early stages of evolution the molecular formations might by chance have had a nonracemic composition. The subsequent selection of molecules of the same chirality type from the racemic surroundings served as the basis for the appearance of a macroscopic excess of one of the antipodes.

Some significant evidence has recently appeared in support of the hypothesis of a spontaneous breaking of mirror symmetry according to which a mirror-symmetric state loses its stability under certain conditions, and there is a spontaneous breaking of mirror symmetry, with an abrupt transition to a chirally ordered state.[38,123-129] According to this theory, the process which leads to the self-organization of chirally pure forms of organic matter is based on cooperative interactions of fluctuations of the antipodal composition of the medium in the course of the set of physicochemical transformations which determined the formation of the first living systems. This question thus lies at the core of the problem of a spontaneous breaking of symmetry, which is being discussed widely in natural science today.

Ideas of a spontaneous breaking of symmetry play an important role in the theory for such phenomena as the phase transitions which lead to ferromagnetism, superconductivity, superfluidity,[130,131] and the generation of coherent radiation of various types.[39] The same ideas underlie modern conceptions of the properties of the physical vacuum[132] and the evolution of the universe in the "hot model"[133] and also the modern theory of the interactions of elementary particles.[134] Spontaneous symmetry breaking is the foundation of a theory for the evolving of spatial and temporal order in chemical and biochemical processes which is being developed in studies by Prigogine's school,[40] and it is the starting point for a new direction in science: synergetics.[39] Such key problems in biology as morphogenesis and differentiation and questions of population dynamics actually reduce to spontaneous breaking of symmetry.[135,136] Even the very appearance of life has been studied from this standpoint.[137]

In addition to the common concept, these problems are tied together by a common mathematical apparatus: bifurcation theory.[39,40,138]

General physical reasons for the breaking of mirror symmetry in the evolution of organic matter have been established successfully on the basis of the ideas and methods of the theory of nonequilibrium processes (dissipative structures).[38,124-129] From this standpoint, the reason for the deracemization of the original organic medium should not be sought in the form of any *a priori* differences in the evolution dynamics of the *levo* and *dextro* mirror-isomer molecules. The symmetry breaking is based on an instability of the racemic state, because of which any, arbitrarily small fluctuations which result in a deviation of the concentration of the isomers from the racemate are autocatalytically amplified and become capable of leading to the essentially complete dominance of one of the isomer forms in the final state of the evolutionary process in the stage of prebiological evolution.

The hypothesis of a spontaneous breaking of mirror symmetry can be described by the following scheme:

| | Statistical fluctuations of the ratio of antipodes | |
|---|---|---|
| Primeval racemic soup | Development and intensification of an asymmetry of the initial state in physicochemical processes | Chiral purity of prebiosphere |

We wish to stress that according to the hypothesis of spontaneous deracemization the repetition of the entire set of events which led to the appearance of chiral purity and then life on earth could be equally successful in leading to a biosphere which uses D-amino acids and L-sugars.

This scenario has recently been winning increasing recognition, some of it from supporters of the idea that an advantage factor of a fundamental nature (weak neutral currents or polarized radiation) had a decisive influence. These authors invoke the idea of a spontaneous deracemization for an intensification of an advantage factor in the course of a nonequilibrium phase transition from a racemate to a chirally ordered medium.[139,140]

A spontaneous breaking of mirror symmetry during the crystallization of solutions of optically active compounds was in fact observed by Pasteur.[141] Pasteur was the first to

observe that certain conditions must be satisfied for this event to happen: If the crystallization goes at a temperature below a critical temperature (for the given compound), chirally pure crystals will precipitate, but at temperatures above the critical temperature the crystals which precipitate from solution will be racemic.

Morozov *et al.*[9] offered a theoretical explanation for this phenomenon. Working from the theory of regular solutions, they showed that a spontaneous separation of a racemic mixture of antipodes is caused under critical conditions by a stereoselectivity of the interactions of the isomer molecules of different chirality (the difference between the interaction energies of the isomers is $E_{LL} = E_{DD} \neq E_{LD}$). The transition from joint crystallization to separate crystallization is associated with a disorder-order transition.

The idea that stereoselective, cooperative interactions of antipodes which lead to the appearance of a positive feedback through the chiral order play a dominant role also underlies the scenario of a spontaneous breaking of the mirror symmetry of organic matter in the course of chemical evolution. Already at the earliest stages of prebiological evolution, a sort of "phase transition" which deracemized the "primeval soup" occurred.

### 6.1. Model for the spontaneous breaking of mirror symmetry

Possible models for transformations of isomer molecules for representing spontaneous deracemization have been the subject of active research (e.g., Refs. 142–147) in recent decades. The general requirements imposed on models of this type, regardless of the specific realizations and details, however, were established in Refs. 38 and 124–129. Looking back at Table III in §4, we easily see that any model for spontaneous symmetry breaking must contain a deracemizing block

$$\mathrm{L} + \mathrm{D} \rightarrow \mathrm{A} \tag{36}$$

or

$$\mathrm{A} + 2\mathrm{L} \rightarrow 3\mathrm{L}, \quad \mathrm{A} + 2\mathrm{D} \rightarrow 3\mathrm{D} \tag{37}$$

(blocks X and XI in Table II). We wish to stress that reactions (36) and (37) may actually conceal complex chains of multistep transformations which effectively reduce to these reactions.

The model which has won the greatest popularity, and which was originally proposed by Frank[148] (Table III), is usually described in the following way in the modern literature:

$$\mathrm{A}+\mathrm{B} \xrightarrow{k_1^{\mathrm{L}}} \mathrm{L}, \quad \mathrm{A}+\mathrm{B} \xrightarrow{k_1^{\mathrm{D}}} \mathrm{D}, \tag{38a}$$

$$\mathrm{A}+\mathrm{B}+\mathrm{L} \underset{k_{-2}^{\mathrm{L}}}{\overset{k_2^{\mathrm{L}}}{\rightleftharpoons}} 2\mathrm{L}, \quad \mathrm{A}+\mathrm{B}+\mathrm{D} \underset{k_{-2}^{\mathrm{D}}}{\overset{k_2^{\mathrm{D}}}{\rightleftharpoons}} 2\mathrm{D}, \tag{38b}$$

$$\mathrm{L}+\mathrm{D} \xrightarrow{k_3} \mathrm{A}', \tag{38c}$$

where $k_i^{\mathrm{L,D}}$ are the rate constants of the corresponding reactions. [Frank's original model did not have step (38a) or the inverse reactions in step (38b)]. We will use this model to demonstrate the basic features of the scenario of spontaneous deracemization (the bifurcation scenario).

In terms of the variables $\eta$ and $\theta = (k_2/2k_1)(x_{\mathrm{L}} + x_{\mathrm{D}})$, the dynamic equations corresponding to model (38) take the form ($k_i^{\mathrm{L}} = k_i^{\mathrm{D}} = k_i$)

$$\begin{aligned} \frac{d\eta}{d\tau} &= -\frac{\rho}{\theta}\eta + a\theta(\eta - \eta^3), \\ \frac{d\theta}{d\tau} &= \rho + \rho\theta - b\theta^2 - a\theta^2(1-\eta^2); \end{aligned} \tag{39}$$

here

$$\tau = k_2 Q t, \quad Q = \frac{4k_1 k_{-2}}{k_2^2(k_3 - k_{-2})},$$

$$\rho = \frac{x_{\mathrm{A}} x_{\mathrm{B}}}{Q}, \quad a = \left(\frac{k_3}{k_{-2}} - 1\right), \quad b = \left(\frac{k_3}{k_{-2}} + 1\right).$$

Note that the equation for $\eta$ has a characteristic structure of the type $\alpha(\theta)\eta - \beta(\theta)\eta^3$. We choose $\rho = x_{\mathrm{A}} x_{\mathrm{B}}/Q$ ($x_{\mathrm{A}}$ and $x_{\mathrm{B}}$ are the concentrations of the achiral predecessors) as a controlling parameter. It is easy to see that there exists a value $\rho = \rho_c$ such that at $\rho < \rho_c$ (the subcritical region) the only stable state of system (38) is a racemic state ($\eta = 0$). When the bifurcation point, $\rho = \rho_c$, is reached, this state loses its stability, and two stable mirror-image states appear in the transcritical region, $\rho > \rho$ :

$$\eta_+^{(s)} = -\eta_-^{(s)} = \left(1 - \frac{\rho_c}{\rho}\right)^{1/2}$$

(the bifurcation diagram is shown in Fig. 16).

We wish to stress that the formation of asymmetric states $\eta_-^{(s)}$ and $\eta_+^{(s)}$ (a deracemization of the system) is not related to the action of an advantage factor (as, for example, in systems of a neutral type); it is instead a consequence of the dynamic properties of the system itself and the processes by which the mirror isomers undergo transformations. If the system is initially in a racemic (on the average) state, the probability for finding it in state $\eta_+^{(s)}$ is equal to the probability for finding it in the state $\eta_-^{(s)} = -\eta_+^{(s)}$. In the scenario of a spontaneous breaking of mirror symmetry, the "sign" of the chiral purity of the prebiosphere is therefore a result of a memory of a random selection of the sign of a fluctuation, $\mathrm{sign}(\eta^{(s)}) = \mathrm{sign}(\eta_0)$, of the initial state.[38,128,129]

### 6.2. Intensification of an advantage factor in the course of spontaneous deracemization

A question which has been the subject of an active debate recently is whether an advantage factor stemming from weak neutral currents could determine the sign of the chiral purity of the biosphere (see §5 and, for example, Refs. 38, 108, and 149–155 and the bibliographies there). It has been suggested that systems which are capable of a spontaneous deracemization are capable of intensifying even such weak advantage factors. Furthermore, Kondepudi and Nelson[151-153] have advanced a hypothesis of an anomalously high sensitivity of cooperative chiral systems of the type in

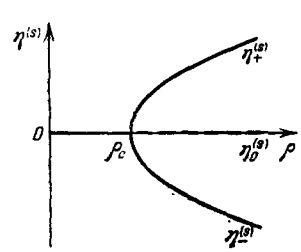


FIG. 16. Bifurcation diagram for Eq. (39).

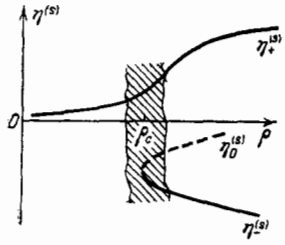


FIG. 17. Bifurcation diagram for system (38) in the presence of an advantage factor. The hatching shows the strong-field region.

(38) if they pass through the critical point slowly. It has been suggested that because the dynamics of the system is of such a nature even a negligibly small advantage factor ($g \sim 10^{-17}$), even in the presence of fluctuations, would be capable of determining the sign of the chirality of the final state of the system. Physically, therefore, the question of an intensification of an advantage factor in systems of the deracemizing type reduces to the question of a competition between the advantage factor and statistical fluctuations.

In the presence of an advantage factor, the dynamic equations corresponding to system (38) take the form

$$\begin{aligned} \frac{d\eta}{d\tau} &= \frac{\rho}{\theta}(g-\eta) + a\theta(\eta-\eta^3), \\ \frac{d\theta}{d\tau} &= \rho + \rho\theta - b\theta^2 - a\theta^2(1-\eta^2), \end{aligned} \tag{40}$$

where $g = (k_1^{\mathrm{L}} - k_1^{\mathrm{D}})/(k_1^{\mathrm{L}} + k_1^{\mathrm{D}})$, and the notation is otherwise that of (39). The bifurcation diagram (Fig. 17) corresponding to (40) differs from the bifurcation diagram for the case in which the advantage factor is zero. Analysis shows that the action of the advantage factor results in substantial changes of $\eta^{(s)}(\rho)$ only in the region of a "strong field," $|\rho/\rho_c - 1| \sim g^{2/3}$. Outside this region (in a "weak field"), the changes in $\eta^{(s)}(\rho)$ are small, $\sim g$. It is not difficult to see that an advantage factor selects one branch of stable steady states, namely $\eta_+^{(s)}$ in the case $g > 0$. Consequently, if a chemical system which starts from a state which is racemic (on the average) reaches $\eta_+^{(s)}$, despite statistical fluctuations, the role of the advantage factor in determining the sign of the chirally ordered state would naturally be assumed to be governing. It was shown in Refs. 154 and 155 that the mechanism for the intensification of an advantage factor in the strong-field region is quite different from that in the weak-field region.

In the weak-field region ($\rho \gg \rho_c$), even though the racemic state does fall in the region of attraction of steady state $\eta_+^{(s)}$, under the condition $\rho \gg \rho_c$ the boundary $\eta_0^{(s)}$ of the attraction region of the alternative state $\eta_-^{(s)}$ is a distance $\sim g$ away from the value $\eta = 0$. Accordingly, the small value of $g$ makes the problem of an intensification of the advantage factor primarily a problem of the "preparation" of an initial state. It is not difficult to see that an effective intensification can be expected only if the fluctuation amplitude $\sigma_\eta^{1/2}$ in the initial state is much smaller than $g$ (Refs. 38 and 149). Since the amplitude of the fluctuations in the chiral polarization is determined by the reserve of chiral material, $N_x$ ($\sigma_\eta = N_x^{-1}$), with $g \sim 10^{-17}$ an intensification would be possible only in systems of "global" scale[38,149,156]:

$$N_x \gg g^{-2} \sim 10^{34}. \tag{41}$$

In the opposite case ($N_x \ll g^{-2}$) the probabilities for reaching steady states $\eta_+^{(s)}$ and $\eta_-^{(s)}$ differ by an amount $\sim (g/\sigma_\eta^{1/2}) \ll 1$. The meaning of condition (41) is simple: The amplitude of the fluctuations in the chiral polarization in a racemic medium suppresses the advantage factor in systems of smaller scale, and the sign of the chiral polarization of the final state is determined by the fluctuations, rather than by the advantage factor.

Estimate (41) was derived under the assumption of a spatially homogeneous system. In the weak-field region, however, the time scale of the evolution of the system is short, and a possible heterogeneity of such large systems should be taken into consideration. Zel'dovich and Mikhaĭlov[157] studied the effect of weak neutral currents on a cooperative chiral system of the type in (38) with spatial diffusion. They showed that, even if the medium had by chance broken up into "domains" with different chirality signs in the earliest stage of the evolution, the advantage factor stemming from weak neutral currents could not have withstood diffusion and would not have been capable of determining the chirality of the entire prebiosphere.

In the strong-field region, i.e., in the region $|\rho/\rho_c - 1| \lesssim g^{2/3}, |\eta| \lesssim g^{1/3}$, the time scales of the variations in the variables $\eta$ and $\theta$ are greatly different: The rate of change of the total concentration of the antipodes ($x_{\mathrm{L}} + x_{\mathrm{D}}$) is substantially higher than the rate of change of the chiral polarization. Consequently, $\theta$ reaches its steady-state value considerably more rapidly than $\eta$ does. This circumstance makes it possible to use the procedure of adiabatic elimination of a fast variable to reduce the system of equations (40) to a single equation describing the dynamics of the order parameter $\eta$ (Refs. 154 and 155):

$$\frac{d\eta}{d\tau} = -A\eta^3 + A\left(\frac{\rho}{\rho_c} - 1\right)\eta + Cg, \tag{42}$$

where

$$A = \frac{k_3 - k_2}{2k_3}, \quad C = \frac{k_3 - k_2}{2k_{-2}}.$$

In the Langevin approach, the stochastic equation corresponding to (42) is

$$\frac{d\eta}{d\tau} = -A\eta^3 + A\left(\frac{\rho}{\rho_c} - 1\right)\eta + Cg + \varepsilon_\eta^{1/2}\xi_\eta(\tau), \tag{43}$$

where $\varepsilon_\eta^{1/2}\xi_\eta(\tau)$ is a white noise with a zero mean and an amplitude $\varepsilon_\eta^{1/2}$. We wish to stress, however, that a description of the dynamics of system (40), evolving from a racemic state, on the basis of Eq. (43) is possible only in the strong-field region $|\rho/\rho_c - 1| \lesssim g^{2/3}$, $|\eta| \lesssim g^{1/3}$ and at times $\tau \lesssim g^{-2/3}$. Outside this region the evolution of the system should be analyzed on the basis of the system of equations (40), with fluctuations.

Before we move on to a study of the mechanism for the intensification in the strong-field region we note that a racemic state ($\eta = 0$) reaches the zone of attraction of steady state $\eta_+^{(s)}$, but its distance from the boundary $\eta_0^{(s)}$ of the attraction zone of $\eta_-^{(s)}$ is no longer $\sim g$, as in the case of a weak field. Instead, this distance is $\sim g^{1/3}$. Consequently, if the fluctuation amplitude in the initial racemic state satisfies $\sigma_0^{1/2} \ll g^{1/3}$, the system as a whole is in the attraction zone of $\eta_+^{(s)}$, distinguished by the advantage factor. In principle, the condition $\sigma_0^{1/2} \ll g^{1/3}$ is not difficult to satisfy. The amplitude of the fluctuations in the chiral polarization, $\sigma_0^{1/2}$, is deter-

mined by the initial number of chiral particles: $\sigma_0^{1/2} = N_x^{-1/2}$ ($N_x = N_A V\theta$, where $N_A$ is Avogadro's number, and $V$ is the volume of the system). For systems of laboratory scale ($N_{ch} \sim 10^{24}$) and $g \sim 10^{-17}$ we have $\sigma_0^{1/2} \sim 10^{-12}$; this figure is clearly smaller than $g^{1/3} \sim 10^{-6}$. The problem of an intensification of an advantage factor in the strong-field region in the case $N_{ch} > g^{2/3}$ thus reduces to an analysis of the dynamics of the mean value of the chiral polarization, $\bar{\eta}(\tau)$ and its variance $\sigma(\tau)$.

The evolution of the chiral polarization in a region spanning nearly the entire interval $|\eta| \lesssim g^{1/3}$ (except for a neighborhood $\sim g^{2/3}$ of the steady-state values $\eta^{(s)} \sim g^{1/3}$) is determined by an equation which is considerably simpler than (43):

$$\frac{d\eta}{d\tau} = Cg + \varepsilon_\eta^{1/2}\xi_\eta(\tau). \tag{44}$$

The Fokker-Planck equation corresponding to (44) is

$$\frac{\partial}{\partial\tau} P(\eta, \tau) = -\frac{\partial}{\partial\eta}(CgP(\eta, \tau)) + \frac{1}{2}\varepsilon_\eta \frac{\partial^2}{\partial\eta^2} P(\eta, \tau). \tag{45}$$

For $g = 10^{-17}$, this equation is inapplicable only in a very small neighborhood of values of $\eta^{(s)}$), amounting to only $10^{-6}$ of the total range of $\eta$ in the strong-field region.

From (45) we find equations for the mean value of the chiral polarization, $\bar{\eta}(\tau)$, and its variance $\sigma(\tau)$:

$$\frac{d\bar{\eta}}{d\tau} = Cg, \quad \frac{d\sigma}{d\tau} = \varepsilon_\eta. \tag{46}$$

Hence

$$\bar{\eta}(\tau) = Cg\tau, \quad \sigma(\tau) = \varepsilon_\eta\tau \quad (\sigma_0 = 0). \tag{47}$$

The "signal-to-noise ratio" $N = \bar{\eta}(\tau)/\sigma^{1/2}(\tau)$ which characterizes the amplification of the advantage factor (the "signal") against the background of fluctuations (the "noise") therefore depends on the time in accordance with (see also Ref. 153)

$$N(\tau) = Cg\varepsilon_\eta^{-1/2}\tau^{1/2}. \tag{48}$$

In the strong-field region, the mechanism for the intensification of the advantage factor is thus a buildup of this factor, and it is completely equivalent in terms of physical meaning to the gradual-evolution scenario. As was shown in Refs. 154 and 155, an intensification of an advantage factor against the background of fluctuations occurs in precisely the same way in systems of the neutral type. This conclusion seems more natural than unexpected since it is the advantage factor which plays the dominant role in the dynamics of the system throughout the strong-field region. On the other hand, the contribution of the nonlinear $\eta^3$ (deracemizing) terms is negligibly small far from the steady states (incidentally, the same is true of the contribution of the linear terms). Consequently, cooperative systems do not have an anomalously high sensitivity to an advantage factor near the critical point.

The amplification of the advantage factor in the strong-field region depends not only on $g$ and $\varepsilon_\eta$ but also on the time ($T$) which the system spends in this region, according to relation (48). For a given advantage factor with a measure $g$, the time $T$ cannot exceed $\tau \sim g^{-2/3}$. The maximum permissible value of the signal-to-noise ratio $N_{max}$ is given by

$$N_{max} = Cg\varepsilon_\eta^{-1/2}T^{1/2} = Cg^{2/3}\varepsilon_\eta^{-1/2}. \tag{49}$$

In contrast with neutral systems, in which the "buildup" effect operates only for sufficiently weak racemizing processes,[154,155] the possibilities for an intensification of an advantage factor in the strong-field region are limited by the time which the system spends in this region, which is, in order of magnitude, $|(\rho/\rho_c) - 1| \sim g^{2/3}$ and exceedingly short for very small advantage factors. As a result, an effective intensification requires that the parameters of the system be rigidly fixed over a long time $\sim T$. It might appear that the problem could be circumvented by passing through the neighborhood of the critical point (the strong-field region) by varying the control parameter at some very low rate $\gamma$. Let us estimate that rate of passage of the system through this region for which the time spent in it, $T$, is sufficient for the buildup of the advantage factor ($N > 1$). Assuming $\tau = \Delta\rho/\gamma$, we find from (48) ($\Delta\rho \lesssim g^{2/3}$)

$$N = Cg^{4/3}\varepsilon_\eta^{-1/2}\gamma^{-1/2}. \tag{50}$$

We should stress that since the buildup effect is determined exclusively by the time $T$ (at given values of $g$ and $\varepsilon_\eta$) the quantity $\gamma$ cannot be chosen arbitrarily: It is rigidly set by the time $\tau \sim T$.

In analyzing the intensification of an advantage factor in a scenario for the onset of chiral purity of the prebiosphere, which is required for the next step in the origination of life—the formation of self-replicating structures—we need to recall that we should be thinking of an intensification of such a nature that the final state of the medium is chirally pure ($\eta = 1$). This statement means that at least the final step of the evolution of the chemical system must occur in the weak-field region. It might seem that if the critical point were passed slowly we could expect a buildup of the advantage factor sufficient to fix the system near $\eta_+^{(s)}$. However, the strong-field region for the advantage factor stemming from weak neutral currents is so narrow that at a rate of passage capable of leading to a buildup of the advantage factor a chirally pure state would be impossible to reach. The analysis of Ref. 153 shows that even if the chemical system has parameter values which are favorable for the hypothesis of slow passage over the age of the earth ($t = 4.5 \cdot 10^9$ yr), at the rate of passage which was proposed by the authors ($\gamma = 3.2 \cdot 10^{-17}$ M$^2$/s) which provides an adequate buildup of the advantage factor, the system is in a region in which the chiral polarization which can be attained does not exceed the small value $\lesssim 10^{-2}$. This value is of course unacceptable from the evolutionary standpoint. The hypothesis of a slow passage requires the further assumption of some extremely specific conditions, which would make possible a sharp transition of the system out of the strong-field region far beyond the critical point. Until there are grounds for making such assumptions, we should recognize that there is no solid evidence for a governing role of weak neutral currents in the passage of biomolecular chirality either by an evolutionary path or by a bifurcation path.

We should thus recognize that intensification does not save the hypothesis that a global advantage factor plays a decisive role in the establishment of chiral purity. The fact that specifically L-amino acids and D-sugars are used in the earth's biosphere is a matter of chance, despite the fact that these molecules are singled out by the advantage factor due to weak neutral currents. It appears that a biosphere based on D-amino acids and L-sugars could have arisen equally

successfully in the course of the chemical evolution on the earth.

## 7. PHYSICAL CONDITIONS FOR A DERACEMIZATION OF THE PREBIOSPHERE

The critical parameters which determined the transition to a chirally pure prebiological medium are caused by the state of this medium, i.e., by its physicochemical characteristics. The controlling parameter which we introduced in §6 does indeed have a fairly complex structure:

$$\rho = \rho\,(x_A,\ x_B,\ \ldots,\ \{k_i^{L,\,D}\}),$$

In other words, it depends on the concentrations of the initial products (substrate) A and B, and through the constants of the elementary interactions it depends on the stereoselectivity of processes involving the antipodes, the temperature of the medium, the pH, etc. Consequently, the possibility of deracemization is determined by the state and physical parameters of the initial racemic "primeval soup".

In the scenario of a nonequilibrium phase transition (the bifurcation scenario) one can formulate a criterion which expresses the ability of a medium to undergo an irreversible breaking of mirror symmetry, i.e., the possibility that the necessary prerequisites for the origination of life can appear in the medium. This criterion is the expectation time of the beginning of an irreversible deracemizaion of a prebiological medium.[128,129,158,159]

The existence of a nonzero expectation time follows from some qualitative considerations to which we now turn.

Let us assume that a system (medium) has reached the critical conditions. A chiral polarization will then begin to develop because of some individual fluctuation at a time $t_{cr} + \tau_0$ ($t_{cr}$ is the time at which the critical conditions are reached, and $\tau_0$ is the typical expectation time for an individual fluctuation in the medium). In principle, this development can terminate in complete deracemization. If, over the time required here, other fluctuations do not arise, or if they arise only rarely, and if the distribution corresponding to fluctuations of the chiral polarization is narrow (if the probability that another large fluctuation of the opposite sign will follow soon after the first fluctuation is small), then the broken-symmetry state generated by the first fluctuation will propagate throughout the accessible medium. In this case the expectation time is $\tau_{ex} = \tau_0$. If, on the other hand, the fluctuations are frequent, and their distribution broad (if there is a fairly high probability that any fluctuation will soon be followed by another fluctuation which is capable of "reversing" the symmetry breaking), the chiral polarization will oscillate in a random way around zero (a racemic state) until, at some time $\tau_{ex} + t_{cr}$, a large "critical" fluctuation appears, at which point a stable evolution to a chirally pure state of the medium begins.

Since the phases differ only slightly from each other near the phase-transition point (for either a first-order or second-order transition), there is the possibility that a large nucleating region of the less symmetric phase will form inside the more symmetric phase. Let us estimate $\tau_{ex}$ under the following assumptions. We assume that in the initial symmetric medium some nucleating regions of a new phase with a broken symmetry arise as a result of fluctuations. We denote the time scale for the appearance of such a nucleating region by $\tau_0$, while the variance of the fluctuations in the number of chiral particles in a nucleating region is $\sigma_0$. We assume that after $t$ the dynamics of the chiral polarization obeys the following very simple equation for deracemizing processes near the critical point (with a vanishingly small advantage factor):

$$\frac{d\eta}{d\tau} = \eta - \eta^3.$$

For an estimate, we can reduce the procedure of incorporating the effect of the set of such fluctuations to replacing $\eta$ by its mean value and adding to the right side of the equation a racemizing term, which stems from the stochastic nature of the processes in the system. It can be shown that this term is $(\sigma_\theta/k_0\tau_0)\eta$ in the case at hand.[129,158] From the bifurcation equation for the dynamic equation for $d\bar{\eta}/d\tau$ modified in this manner we find that deracemization sets in if (on the average, over the system)

$$\Lambda \equiv \frac{k_0\tau_0}{\sigma_\theta} > 1 = \Lambda_{cr}\,.$$

If, on the other hand, the relation $\Lambda < 1$ holds on the average, and if this parameter is a random quantity for each individual nucleating region—specifically, if $\Lambda_i = \lambda_i\Lambda$, where $\lambda_i$ is some random function—then the breaking of the symmetry begins with the formation of a nucleating region with $\lambda_{cr} > 1/\Lambda$. Since $\lambda_{cr}$ for the $\lambda_i$ distribution is a large quantity, we can assume that it obeys the statistics of extreme values, which predicts the following relationship between the amplitude of a fluctuation and its expectation time[160]:

$$x - \bar{x} = \sigma_0 \ln \frac{t}{\tau_0}\,.$$

We thus find the following expression for the expectation time for the beginning of deracemization:

$$\tau_{ex} = \tau_0 \exp \frac{\sigma_\theta}{k_0\tau_0}\,. \tag{51}$$

In the time interval between $t_{cr}$ and $t_{cr} + \tau_{ex}$ the prebiological medium exists as a metastable phase with conserved symmetry and with an increasing mass of chiral material, which is characterized by the value of $\theta$.

The quantities which determine $\tau_{ex}$, i.e., $\sigma_\theta$, $\tau_0$, and $k_0$, obviously depend on the state of the medium. The relationship between these quantities and the state of the medium was analyzed in Ref. 159. The model developed in that paper predicts

$$\begin{aligned} \sigma_\theta &= \left(\frac{4}{3}\pi R_c^3\rho_0\right)^{1/2}, \\ \tau_0 &= \frac{4}{3}\pi R_{cr}^3 J, \\ k_0 &= 4\pi\omega\gamma R_c^2 I, \end{aligned} \tag{52}$$

where $R_{cr}$ is the critical size of a nucleating region, $J$ is the rate at which nucleating regions form, and $I$ is the flux of $\theta$ across the surface of the nucleating region. Assuming that the laws governing the formation of nucleating regions of a new phase apply in this case,[161] we find the following expression for $\tau_{ex}$ (the detailed calculations are given in Ref. 159):

$$\tau_{ex} = \tau_0 \exp\left[\frac{\delta}{\omega\gamma}\left(\frac{\rho}{\rho_0}\right)^{\mu}\left(\frac{\Delta H}{k_B T}\right)^{\nu}\right], \tag{53}$$

where $\rho$ and $\rho_0$ are the density of chiral matter in the medium and in the nucleating region, respectively, $\Delta H$ is the

binding energy of the molecules in the nucleating region, and the dimensionless quantities $\delta$ and $\mu$ depend on the state of the matter in the medium. For a gaseous phase we would have $\delta = 10^3$ and $\mu = 1$; for a solution we would have $\delta = 10^{-1}$ and $\mu = 2/3$. Here also, $\nu = 9/4$; $\omega = \exp(\Delta H / k_B T)$ is the so-called attachment coefficient in nucleation theory; and the coefficient $0 < \gamma < 1$ is a measure of the selectivity of the interaction of the molecules of the nucleating region with the isomer molecules of the medium.

We have a few comments regarding certain estimates which follow from expression (53). First, for the early stages of the evolution of the universe—the hadron era, the lepton era, and the baryon era, we find $\tau_{ex} > 10^{14}$ s, which is a time incomparably longer than the age of the universe ($\tau \sim 10^{17}$s). This conclusion, of course, is what we should have expected.

Second, in the scenario which has life arising from a "primeval soup" on a planet like the earth (with $\rho \sim 10^{21}$ particles/cm$^3$ and $T^{(0)} = 300$K) we would have $\tau_{ex} \sim 10^{13}$–$10^{14}$ s. This time does not exceed a few percent of the duration of the prebiological evolution. In the same scenario there is an upper limit on the binding energy of the molecules in a nucleating region, and under this restriction $\tau_{ex}$ does not exceed the age of the earth. Specifically, with $\Delta H / kT \lesssim 30$ we find $\tau_{ex} < 4 \cdot 10^9$ yr. We might note that this estimate of $\Delta H$ corresponds to the energy of hydrogen bonds. We thus see that even some very simple estimates demonstrate fairly accurately (in view of the crudity of the assumptions) that the physical conditions on the early earth were more suitable for the formation of living systems over those times, by means of those interactions, and from those particles (estimates of the particle sizes which minimize the expectation time yield $\sim$10-7 cm) which are actually observed.

The expectation time is a criterion which expresses the possibility that life arises under certain conditions or others on certain celestial objects or others. Specifically, if we know the parameters of the medium which are characteristic of the given celestial object (e.g., a planet, a dust-gas cloud, etc.), we can estimate the expectation time for the beginning of an irreversible racemization of the medium. If we find that $\tau_{ex}$ exceeds the age of the celestial object, we should acknowledge that the appearance of life is impossible in this case, since a deracemization of the medium—a necessary prerequisite for the appearance of living structures—does not occur.

The concept of an expectation time for the beginning of a breaking of mirror symmetry makes it possible to move on to the solution of yet another problem which is being debated widely: Was the appearance of life on the earth a consequence of a single event or the result of a competition among several prebiospheres which arose independently? We can approach the resolution of this question along the path of a deracemization of the prebiosphere. The appearance and coexistence of natural habitats within which the chirality of the organic matter has different signs are equivalent to the appearance of a set of competing prebiospheres, i.e., to a multiplicity of nucleation events. If, on the other hand, the deracemization process generated by a critical fluctuation spanned the entire planet, the "act of origination" was unique.

Let us consider a gedanken experiment: We assume that the racemic "primeval soup" has reached a critical state required for a transition to chiral order and occupies two habitats which communicate with each other (e.g., northern and southern hemispheres). We also assume that an advantage factor is operating in each habitat and that the nature and measure of the advantage factor are identical in the two regions, but the signs of the advantage factors are opposite. The action of the advantage factor leads to an excess of one of the antipodes—different ones in the two habitats. If the mixing of matter is sufficiently intense, however, the medium as a whole will remain racemic. Since such a medium is in a state which is unstable with respect to fluctuations of the chiral polarization, the very first critical fluctuation, which appears after a time $\tau_{ex}$, marks the beginning of a deracemization process. We assume even that a critical fluctuation is of such a nature that the reserve of chiral material, $N_{ch}$, satisfies the condition for the dominance of the advantage factor in the formation of the sign of the symmetry breaking: $N_{ch} \gg g^{-2}$. Since the appearance of a critical fluctuation is equally probable in each of the two habitats, however, we should recognize that the sign of the chirality of the prebiosphere will be determined with equal probabilities by the sign of the advantage factor of each of the habitats. In other words, it will be random for the prebiosphere as a whole. It is not difficult to see that the result of this gedanken experiment does not depend on the number of habitats which we consider or on the nature of the local advantage factor. Since the "colonization" of a medium by a critical fluctuation occurs in a time $\sim 10^2$–$10^4$ yr (mixing due to flows, etc.), and since this time is substantially shorter than the expectation time for the critical fluctuation which is the next to follow the first, $\tau_{ex} \sim 10^7$ yr, we can confidently say that the deracemization of the prebiosphere was a result of a single event, rather than a consequence of a set of local deracemization events (this is true regardless of whether there is an advantage factor).

## 8. "COLD PREHISTORY" OF LIFE

In the preceding sections of this review we have discussed various physical aspects of the appearance of chiral purity in the prebiological medium on the basis of the so-called warm (terrestrial) scenario for the origin of life. In this section of the paper we take a totally different approach to the problem of the origin of life: the so-called cold (extraterrestrial) scenario, which assumes that at least certain stages of the process by which life originated occurred in space.

We accordingly turn to some recent studies which have revived interest in the hypothesis of panspermia, which was advanced by Arrhenius at the beginning of the present century and which might seem to have been totally forgotten. As we mentioned back in the Introduction, recent geological discoveries have shrunk the time allotted by nature to prebiological evolution by a factor of essentially 10: from $2 \cdot 10^9$ yr to $2 \cdot 10^8$ yr. As a result, doubt has arisen that such a short time interval would be sufficient for the prebiological stage of the origination of life—from small molecules to the formation of structures capable of self-reproduction. On the other hand, a variety of organic compounds, some extremely complex—ranging up to amino acids and oligomers—have been observed in space.[13,14] As a result, extraterrestrial scenarios for the origination of life have appeared, ranging from Crick's hypothesis of a "directional panspermia"[162] to Hoyle and Wickramasinghe's hypothesis of "living interstel-

lar clouds."[163,164] Crick's hypothesis is actually a variant of a warm scenario, but played out on some planet other than the earth. The second hypothesis, on the other hand, is of a fundamentally different nature: It puts the basic stages of the process by which life originated, including the formation of self-reproducing structures, in open space—more precisely, in dark dust-gas clouds. The possibility of a "cold prehistory of life" was first raised by Goldanskiĭ (see Refs. 165–167 and the bibliographies there), who worked from a low-temperature quantum limit which he had discovered on the rate of chemical reactions. It is because of these astrophysical discoveries and the experimentally confirmed existence of a nonzero rate of chemical reactions at low temperatures that we must take a closer look at the hypothesis of a cold prehistory of life.

An extraterrestrial scenario based on the present understanding of the chemistry of deep cold and on data on the composition of the interstellar medium might take the following (extremely sketchy) form.

In dark dust-gas clouds (with a lifetime $\sim 10^5$–$10^6$ yr, with typical dimensions $\sim 10^{17}$–$5\cdot 10^{19}$ cm, with a temperature $T^{(0)} \sim 20$ K, with a total weight of dust amounting to $\sim 10^{-2}$ of the weight of the gas, with dust grains $\sim 10^{-5}$ cm in size consisting of a silica or graphite core covered with a "coat" of dirty ice $\sim 10^{-6}$ cm thick containing CO, $NH_3$, HCN, etc.), progressively more-complex organic compounds—ranging up to the predecessors of biologically important molecules—could be synthesized in chemical processes stimulated by long-range protons, hard UV radiation, and $\gamma$ radiation, primarily in the dirty-ice coats on the surfaces of the grains.

As a gravitational instability develops in the dark dust-gas cloud, a differentiation of the matter occurs, and a protostar forms. Planetesimals accrete from the dust-gas disk which forms around the star and grow into planets. Consequently, the organic compounds which had formed in the dust-gas cloud can reach the planet by two processes: first, during the accretion of the planet (although the compounds would apparently be subject to fairly intense destruction as the planet was born and also as it warmed up); second, after the planet had formed, through the adsorption of these compounds on the surface of the planet from the surrounding space. The organic compounds which reached the planet in this fashion might then have served as the raw materials for the formation of the "primeval soup."

This hypothesis itself, however (and also conceivable variations on it), would work only in a situation in which a breaking of mirror symmetry of organic matter becomes possible, at least in principle, under the conditions prevailing in space (low temperatures, hard radiation, low densities of matter, etc.). For Hoyle and Wickramasinghe's hypothesis of living interstellar clouds, this requirement becomes more stringent: If living systems are to arise, we would need not simply a breaking of mirror symmetry but a complete deracemization of the medium (otherwise, a crucial property of life—self-replication—could not arise).

Note that there is an important difference between the problems of the breaking of mirror symmetry in the warm and cold scenarios. In a warm scenario, chemical processes go quite rapidly on the evolutionary time scale, and the sign of the chirality is conserved during the chemical transformations of the isomer molecules (the concept of the chirality of an individual molecule has a completely definite meaning). In a "cold" scenario the rates of chemical transformations are exceedingly low, and molecules may repeatedly undergo a change in the sign of their chirality by virtue of an effective tunneling aracemization or racemization induced by hard radiation, for which the time scales are comparable to the rates of the chemical processes themselves. Accordingly, the process L → D in a "cold" scenario may lead to a situation in which the concept of the sign of the chirality of an isomer molecule "gets lost" over the time scales of the physicochemical processes (§3).

The first problem associated with the breaking of mirror symmetry in a "cold prehistory of life" is thus the problem of the stabilization of the chirality of the molecules of the mirror isomers.

### 8.1. Stabilization of the chirality of antipodes in a "cold" scenario

What are the possibilities for stabilization of the chirality of molecules in a "cold" scenario? For an analysis of this question it is convenient to speak in terms of two-level systems.[168]

We first consider the behavior of an isolated chiral molecule under the condition that only tunneling transitions between the L- and D-states of the molecule are possible. We assume that the $x$ axis corresponds to the position of some atom (or group of atoms) or some other collective coordinate of the molecule. In a symmetric potential, $+x$ corresponds to the L-state, and $-x$ to the D-state. Following Ref. 169, we define the operator $\hat{x}$, which gives the position of an atom in the chiral potential

$$\hat{x} = |\mathrm{D}\rangle\langle\mathrm{D}|\, x\, |\mathrm{D}\rangle\langle\mathrm{D}| + |\mathrm{L}\rangle\langle\mathrm{L}|\, x\, |\mathrm{L}\rangle\langle\mathrm{L}|, \tag{54}$$

but

$$\langle\mathrm{L}|\,\hat{x}\,|\mathrm{L}\rangle = -\langle\mathrm{D}|\,\hat{x}\,|\mathrm{D}\rangle = -x_0,$$

i.e.,

$$\hat{x} = -x_0\hat{\sigma}_z, \quad \hat{\sigma}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

where $x_0$ corresponds to a minimum of the D-well in the chiral potential. It was shown in Ref. 169 that for an isolated molecule the expectation value $\langle x\rangle$ of the position of the molecule in the chiral potential satisfies the oscillator equation

$$\frac{d^2}{dt^2}\langle x\rangle + (2\Omega)^2\langle x\rangle = 0, \tag{55}$$

where $\Omega = \langle\mathrm{L}|\hat{H}|\mathrm{D}\rangle/\hbar$ is the typical frequency of the tunneling between the L- and D-states, and $\hat{H}$ is the Hamiltonian of the molecule. (The dependence of $\Omega$ on the parameters of the molecule and the potential is given in §3.) After $t > \Omega^{-1}$, a particle which had been in the L-state at time $t = 0$ is in the D-state as the result of tunneling. Accordingly, over a time $\tau \gg \Omega^{-1}$ the probability that the molecule will be in the L-state is 1/2 (and the probability that it is in the D-state is the same).

However, it has been shown in several papers[168-171] that if chiral molecules interact with an optically inactive medium consisting of a deeply cooled gas of low density, where only binary collisions are significant, stabilization of the chirality of isomer molecules would be possible over times

much longer than $\tau$ under these conditions. The interactions of the isomer with the molecules of the medium have the consequence that the chiral particle behaves as a damped rather than free oscillator. In terms of the position of the atom in the chiral potential, the equation for $\langle x \rangle$ takes the form[169]

$$\frac{d^2}{dt^2}\langle x\rangle + \gamma \frac{d}{dt}\langle x\rangle + (2\Omega)^2 \langle x\rangle = 0, \qquad (56)$$

where the damping parameter $\gamma$ depends on the characteristics of the medium and is given by

$$\gamma = N_0 \frac{\pi v}{K^2} \sum_{J,\, i} \frac{(2J+1)\,\omega_i^J}{(2j_1+1)(2j_2+1)} \langle Ji|\, S_L^{J+} S_D^J - \hat{1}\, |Ji\rangle.$$

The quantity $N_0$ is the number density of the atoms of the medium; $K$ is the relative momentum in the c.m. frame of reference; $j_1$ and $j_2$ are the internal angular momenta of the objects involved in the collision; $\omega_i^J$ are statistical weights; $S_L^J$ and $S_D^J$ are scattering matrices; and $v$ is the velocity of the atoms of the medium. As the result of an interaction with the medium, a particle which was originally in, say, the L-state is "stabilized" in that state:

$$\langle x(t)\rangle = \langle x(0)\rangle \cos(2\Omega t) \exp(-\Omega^2\gamma^{-1}t). \qquad (57)$$

Consequently, although racemization does occur, the time scale for the process, $\tau_r = \gamma/\Omega^2$, increases sharply compared to the racemization time for an isolated particle, $\tau = (2\Omega)$ . The racemization "rate constant" $R =$ depends on the temperature in an extremely nontrivial way (Fig. 18). As a result, even small molecules which are interacting with the medium at low temperatures will spend a long time in a state with a negative chirality and transitions between states with opposite chirality (tunneling racemization) will be suppressed.

### 8.2. The problem of the deracemization of the medium in a "cold" scenario

The very fact that the chirality of a molecule is stabilized at low temperatures by the interaction with the medium is, understandably, an extremely attractive aspect of a cold scenario. One should keep in mind that the problem of the deracemization of the medium as a whole arises here. Specifically, each of the isomer molecules is initially in a state with a definite chirality, i.e., in either the L-state or the D-state. The ensemble of such molecules, however, is probably in a racemic state, and the stabilization of the chirality of each molecule works in favor of racemization in this case.

An excess of molecules of any single chirality (e.g., the L-isomers) could in principle arise as the result of an advantage factor (weak neutral currents or $\beta$ decay), since the potential loses its symmetry by virtue of parity nonconservation, and the L-state becomes preferable from the energy standpoint for amino acids and for the D-isomers of the predecessors of sugars.[98,101] The amplitude of the advantage factor at the low temperatures characteristic of dust-gas clouds increases by 1.5–2 orders of magnitude, and the entropy factor similarly decreases under these conditions.

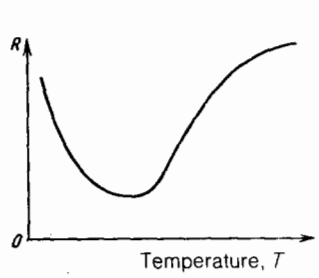


FIG. 18. Temperature dependence of the racemization rate constant $R$.

It should be kept in mind, however, that an intensification of the advantage factor in the scenario of gradual evolution would be possible only in processes of a neutral type, i.e., either in a stereoselective destruction $L \xrightarrow{k^L} A, D \xrightarrow{k^D} A$ caused by polarized radiation or in a steroselective autocatalytic synthesis ($A + L \xrightarrow{k^L} 2L, A + D \xrightarrow{k^D} 2D$), where the difference in constants stems from weak neutral currents (§4 and §5). The first of these processes—destruction—has an extremely severe disadvantage, however: The chiral material is destroyed in the course of the destruction. The loss of molecules is an exponential function of the time:

$$\theta(t) = \theta(0) \exp\left[-\frac{1}{2}(k^L + k^D)\, t\right].$$

The destruction thus leads to a rapid decrease in the number of chiral molecules, so at the extremely low rates of synthesis processes under the conditions prevailing in space this process would be unsuitable for an extraterrestrial scenario.

As was shown in §4, autocatalytic synthesis could lead, under realistic conditions (in the presence of the unavoidable racemizing processes), to only a slight excess of one of the isomers: $\eta_{max} \sim g/k_R$, where $g$ is the measure of the advantage factor, and $k_R$ is an effective rate constant of the racemizing process. Even if we ignore the question of the possible values of $\eta_{max}$, however, we should stress that an autocatalysis process could hardly occur under the conditions prevailing in space. The accumulation of molecules on the surface of dust grains by a prolonged sorption would not save the day, since the molecules would be frozen into the ice "coat", so their mobility would be sharply limited (the probability for bimolecular reactions and for complex chains of reactions required for the occurrence of the autocatalysis would be low).

It would thus be hard to expect that the problem of the breaking of the mirror symmetry of organic matter in a scenario of a "cold prehistory of life" could be solved in a scenario of "gradual evolution" under the influence of an advantage factor. Here we are confronted by the same problem as in a warm scenario: searching for deracemizing processes which lead to a spontaneous breaking of mirror symmetry. This problem is even more serious in a "cold" scenario than it is in a "warm" scenario. However, we do not rule out the possibility that the chemistry of deep cold, or space chemistry—a field which is just beginning to be developed—combined with the ideas of the self-organization of nonequilibrium processes will point out some possible (and unexpected) approaches to the solution of this problem. Our picture of the paths by which life can originate will undoubtedly be enriched as a result.

## 9. CRITICAL LEVELS OF RACEMIZATION OF THE BIOSPHERE

In this section of the review we would like to take up a problem which is in a sense the inverse of the problem of the

appearance of the chiral purity of the biosphere: a possible racemization of the biosphere by long-term racemizing factors.

It is becoming a progressively more urgent matter to analyze the consequences of global influences on the environment, since civilization has developed to a level at which anthropogenic factors can have a most decisive effect on the functioning of the biosphere (Refs. 172 and 173, for example). However, there has been no analysis of the effect of long-term, large-scale influences on one of the fundamental properties of life: its chiral purity. One of the catastrophic consequences of these influences might be the collapse of living nature to the state which preceded its appearance.

As was shown above, a necessary condition for the origination of life on the earth—the appearance of self-replicating systems—is the chiral purity of the organic medium. As systems whose replication is based on the property of complementarity evolve, their chiral purity must be conserved. Otherwise the system will lose its ability to self-reproduce. This statement means that in the stage of the formation of the early biosphere the broken mirror symmetry of the organic medium was inherited by self-replicating systems, was sustained by them, and became fixed as a fundamental property of the bioorganic world. The modern biosphere, as an open system in a mirror-symmetric environment, must therefore maintain its own chiral purity. We already have data which indicate a relationship between the loss of chiral purity of metabolic systems of an organism and the development of pathological states (e.g., Refs. 174–177).

Studying the possibility of destruction of the chiral purity of the biosphere requires constructing a fairly crude but adequate model. The fact that today's biosphere is chirally pure does not by itself give us enough information to model the dynamic laws which lead to this purity. We believe that the missing information can be found by analyzing the reasons for the appearance of chiral purity and the dynamic laws which are responsible for the formation and sustenance of this property throughout evolution, beginning with the stage at which life appeared.

The model which we need is constructed in the following way.[178] The biosphere is represented as consisting of two interacting subsystems P and A, one of which (P) is responsible for the production of chiral matter as a result of the supply of achiral matter S and energy to it from without. In particular, at the present stage of evolution, we could include in subsystem P the plant world, which generates chiral material by photosynthesis. The second subsystem (A) consists of entities $\alpha$ which use the chiral material of subsystem P for their own reproduction. The consumption of the chiral substrate of one of the antipodal forms (for definiteness, the L-form) results in a self-reproduction of $\alpha$, while the consumption of the other form (D) causes entity $\alpha$ to lose this self-reproduction capability, causes the destruction of this entity ($\alpha \to \alpha'$), and causes a transition of $\alpha'$[1] to system P in the form of a racemate. (Processes which lead to the racemization of bioorganic matter and the efficiency of these processes as functions of the external conditions have been studied in Refs. 31–34 and 177, among other places.)

The dynamic laws which control the behavior of subsystem P can be formulated if we assume (as we mentioned above) that these laws are inherited from that stage of the evolution in which there was a spontaneous breaking of the mirror symmetry of the organic medium, and the chiral purity of the medium was attained.

In our very simple model, in which subsystem P is represented by a typical bifurcation scheme, which was analyzed in detail in §4, the dynamic equations are (in dimensionless form)

$$\begin{aligned}
&\frac{d\alpha}{d\tau} = (\eta - \varepsilon)\,\theta\alpha - \frac{\alpha}{T}\,,\\
&\frac{d\alpha'}{d\tau} = (1+\varepsilon)(1-\eta)\,\theta\alpha + \frac{\alpha}{T} - k_0 k'\alpha',\\
&\frac{1}{k'}\frac{d\eta}{d\tau} = \left(\delta\theta - k_0\frac{\alpha'}{\theta} - k_r\right)\eta - \delta\theta\eta^3 + \frac{1}{k'}(1-\eta^2)\,\varepsilon\alpha,\\
&\frac{1}{k'}\frac{d\theta}{d\tau} = \varkappa\theta - \theta^2 + \delta\theta^2\eta^2 - \frac{1}{k'}(1-\varepsilon\eta)\,\theta\alpha + k_0\alpha,
\end{aligned} \tag{58}$$

where $\tau = (k_1 + k_2)t/2$ ($k_1$ and $k_2$ are the rate constants for the replication and destruction, respectively, of entities $\alpha$ during the consumption of the L- and D-isomers), $T$ is the dimensionless lifetime of $\alpha$, $k_r$ is the reduced rate constant for the racemization of the matter of subsystem P, $\varkappa$ is the reduced reserve of the achiral raw material S (and of energy), and $\varepsilon$, $\delta$, $k_0$ and $k'$, are auxiliary parameters of the model. To describe the chiral order of the biosphere we use the quantity $H$, which is related to the variables introduced above by $H = (\alpha + \theta_\eta)/(\alpha + \theta)$.

Analysis of the steady-state solutions of this system of equations furnishes an answer to the question of the existence of critical conditions for the destruction of the chiral purity of the biosphere. There are three possible states for this system. First, there is the state that we see today, which we will call state I: $\alpha > 0$, $\theta > 0$, $H \approx 1$. Second, there is a state in which the entire biosphere is represented by subsystem P, in a chirally polarized state; we will call this state II: $\alpha = 0$, $\theta > 0$, $H = \eta > 0$. Finally, state III is characterized by not only the absence of subsystem A but also by the completely racemic nature of subsystem P: $\alpha = 0$, $\theta > 0$, $H = \eta = 0$. Such a state of the organic medium is characteristic of a prebiological stage of evolution on the earth, before the breaking of mirror symmetry.

Negative anthropogenic influences may affect both subsystem A and subsystem P. The direct effect on subsystem A is trivial. A decrease in the typical lifetime $T$ of entities $\alpha$ to some critical value $\tau_c$ leads to the disappearance of subsystem A, while all the properties of subsystem P are conserved (a transition from state I to state II). However, influences on subsystem P, even if they do not directly affect subsystem A, can lead to equally dramatic consequences for subsystem A. Analysis of the model shows that there exists a critical level of destruction of the chiral purity of the biosphere, i.e., a critical level of the "pollution" of the biosphere with the unnatural isomer form of the molecules, at which the existence of subsystem A becomes impossible. This situation is reached when the influences on subsystem P exceed a certain critical level which is determined by the racemization of the chiral matter, the reserve of a chiral material, etc. In other words, they are directed toward specifically those parameters of subsystem P which are responsible for the formation and sustenance of the chiral purity of the biosphere. The situation is illustrated by Fig. 20, where it corresponds to a transition from branch 1 to branch 2. We will call such a transition a *catastrophe of the loss of chiral purity*. We note, however, that even if such a catastrophe occurs the situation

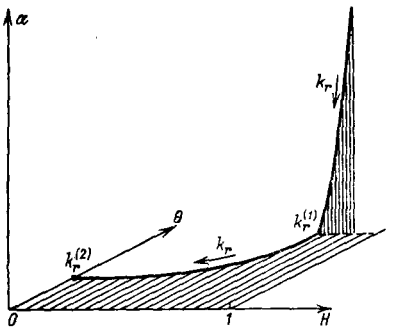


FIG. 19. Dependence of the steady states $(\alpha,H,\theta)$ on the racemization of the chiral substrate. $k_r^{(1)}$—The first critical value of the racemization rate constant $k_r$; $k_r^{(2)}$—the second critical value of $k_r$ (the arrow shows the direction in which $k_r$ increases).

is still "reversible", in a sense, in terms of the possibility of an "evolutionary restoration." After the influences on the biosphere come to an end, the chiral purity of the biosphere will be restored, so the appearance of subsystem A is possible in principle (although it is definitely not obvious that this subsystem will consist of the same entities.

The influences on subsystem P can have even more-catastrophic consequences for the biosphere as a whole. In addition to the first critical level of the influences, which results in the disappearance of subsystem A, there is also a second critical level, at which not only is subsystem A destroyed but there is also a complete racemization of subsystem P (Fig. 19, $k_r \to k_r^{(2)}$, and Fig. 20, the transition from branch 2 to branch 3). The biosphere disappears, and the entire system goes into the state which preceded the nucleation of life: a racemic state of the medium. In the sense indicated above, this transition is completely irreversible: For the beginning of the evolutionary process, nature would again be obliged to wait for a spontaneous breaking of mirror symmetry in the prebiological racemic medium. The reaching of the second critical level of influences and the transition of the biosphere to state III could be called a *collapse of living nature.*

Today we already clearly recognize that long-term negative global influences can lead to the destruction of biogeocenosis at the scale of the entire earth. We would like to point out, however, that additional influences tending to racemize

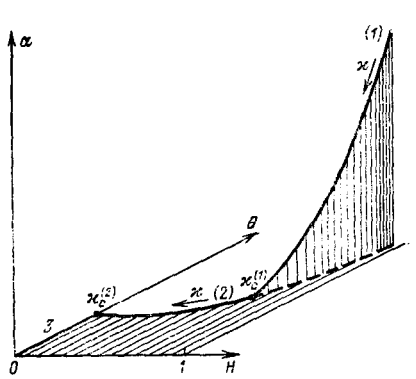


FIG. 20. Dependence of the steady states $(\alpha,H,\theta)$ on the achiral reserve $\varkappa$. $\varkappa_c^{(1)}$—The first critical value of $\varkappa$; $\varkappa_c^{(2)}$—the second critical value of $\varkappa$ (the arrow shows the direction in which $\varkappa$ decreases).

the biosphere may affect the fundamental properties of living nature and, when they reach critical levels, cause an actual disappearance of life from the earth.

## 10. CONCLUSION

It has not been our purpose here to discuss all aspects of the problem of biomolecular chirality. For example, the extremely interesting problem of the biological importance of the chiral purity of the most important biomolecules for the functioning of organisms, normal and pathological, the problem of the maintenance of chiral purity in modern organisms, and the consequences of the contamination of an organism by "unnatural" isomers—all these problems lie outside the scope of this review. The medical and biological aspects of the "asymmetry of protoplasm" are today beginning to attract progressively more attention from specialists in a wide variety of fields of knowledge.

Our basic purposes in this review were to demonstrate the power of physical approaches to the problem of the appearance of the chiral purity of the biosphere and to demonstrate that such approaches make it possible to not only formulate various hypotheses regarding the mechanisms for the breaking of mirror symmetry but also to analyze these mechanisms at qualitative and quantitative levels.

We must not fail to point out that this problem, which seemed until just recently to be a purely biological one, cannot be solved unless we appeal to some very diverse approaches—from ideas regarding the physics of the microworld (weak interactions, parity nonconservation, quantum tunneling) to ideas from mathematical and statistical physics, the theory of nonlinear processes, chemical physics, etc. We believe that the application of these ideas and methods has made it possible to point out paths for solving certain key questions in the problem of the deracemization of the biosphere and the origin of life.

For example, the use of some basic ideas from chemical physics—the science of the kinetics of chemical reactions and of the chemical structure of matter—has led to the extremely important conclusion that the chiral purity of the basic building blocks of life—the sugars and amino acids—arose in the stage of prebiological evolution and is a necessary condition: Self-replication could not arise if this condition were not met. Chiral purity is therefore a relict property which the biosphere has inherited from the stages of chemical evolution of the organic medium on a primitive, prebiological earth.

Analysis of the processes which occur in nonequilibrium chiral systems has made it possible to evaluate critically many hypotheses which link the appearance of chiral purity with the action of an advantage factor and to reach the conclusion that "gradual-evolution" processes under the influence of an advantage factor would not be capable of leading to a pronounced breaking of mirror symmetry in the stage of prebiological evolution.

The most acceptable scenario for the appearance of the chiral purity of the prebiosphere (its deracemization) today is the scenario of a spontaneous breaking of mirror symmetry in which the appearance of this extremely important property of living things is linked with a self-organization of chirality in a "primeval soup". The very fact that the biosphere has chiral purity should be thought of as evidence that nature has successfully carried out an "experiment" on

an absolute asymmetric synthesis of organic compounds with a 100% asymmetric yield in the course of a self-organization process!

Our analysis of the role of advantage factors puts us in a position to discuss possibilities for detecting small advantage factors in cooperative chemical systems. In principle, there are two possibilities: detection in the weak-field region and detection in the strong-field region (§6). The first of these possibilities (according to which chirally pure states, with $\eta \approx 1$, are reached) is limited in a fundamental way by the smallest sufficient size of the chemical chiral system ($N_{ch} > g^{-2}$). Under laboratory conditions ($N_{ch} \sim 10^{24}$), this possibility could be realized only for advantage factors which are not too small ($g > 10^{-12}$). The second possibility stems from the mechanism of an intensification of an advantage factor near a critical point. Whether this possibility can be realized depends primarily on whether it is possible in an experiment to hold rigidly the parameters of the system near the critical point (a slow variation of the controlling parameter in a region with large fluctuations), wait the time required for the buildup of the asymmetry to an experimentally observable value, etc. If the quantity $g$ is such that the time required for the experiment (the time spent by the system in the strong-field region), $T \sim g^{-2/3}$, is reasonable, then by choosing a corresponding low rate of passage through this region one could achieve a buildup of the advantage factor. In principle, this approach could also be taken for systems in which the number of particles is much lower than $g^{-2}$. However, in this case, with $g = 10^{-17}$, for example, we would need to be in a very narrow region near the critical point ($\sim 10^{-12}\rho_c$) for a time $\sim 10^{11}$ s.

We should point out that the experiments carried out to model the process by which asymmetry arose (by which symmetry was destroyed) in chiral systems have so far been limited to essentially only experiments with various advantage factors (and some studies of the relationship between a matrix synthesis of oligonucleotides and the chiral composition of the medium). For the most part, the processes of destruction and catalytic synthesis have been studied. We believe that an experimental search should also be carried out in the direction of realizing systems in which chains of physicochemical transformations create positive-feedback loops through the chiral polarization of the products: systems with a spontaneous breaking of mirror symmetry.

It would also be interesting to see experiments on the process by which the chirality of isomer molecules is stabilized in solids and in the gas phase at low temperatures, to model the conditions of a "cold" scenario.

This list of possible studies of the problem, which are of interest from both the fundamental and applied standpoints, could be continued, but we believe that much joint effort of physicists and chemists from various fields is necessary here. We wish to stress that this problem of the appearance of the chiral purity of the biosphere, which was in fact formulated by Louis Pasteur, still has more unresolved questions than resolved ones, despite a century of research.


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