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College on Methods and Experimental Techniques in Biophysics

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Transparencies

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These are preliminary lecture notes, intended only for distribution to participants.

MIRROR SYMMETRY BREAKING, ORIGIN OF BIOCHIRALITY AND PREBIOTIC EVOLUTION

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OUTLINE OF LECTURES.

Lecture 1.

What is the Biochirality?

Lecture 2.

How many scenarios for the origin of Biochirality can be?

Lecture 3.

Could Biochirality result from the action of any asymmetric factor ?

Lecture 4.

The equation for the origin of Biochirality.

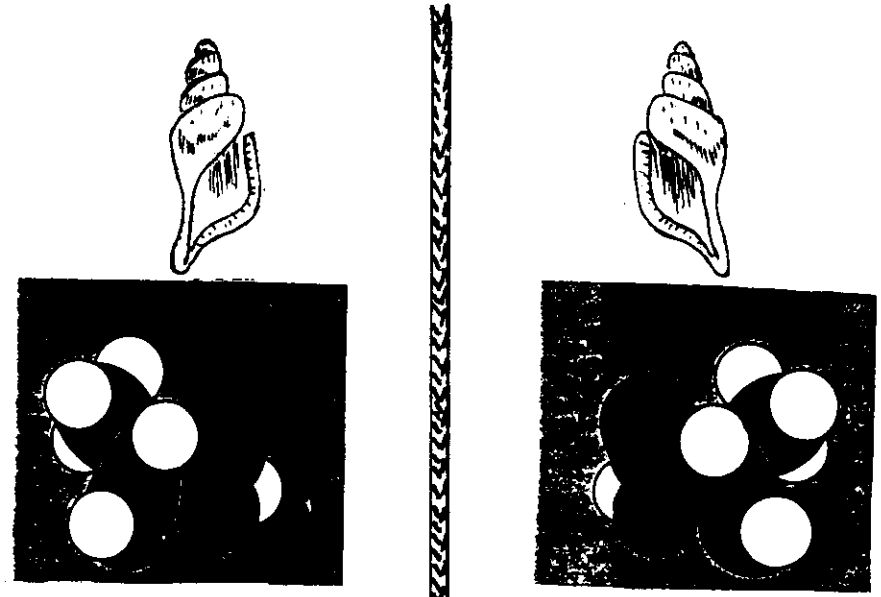
What is the Biochirality?

What is Chirality?

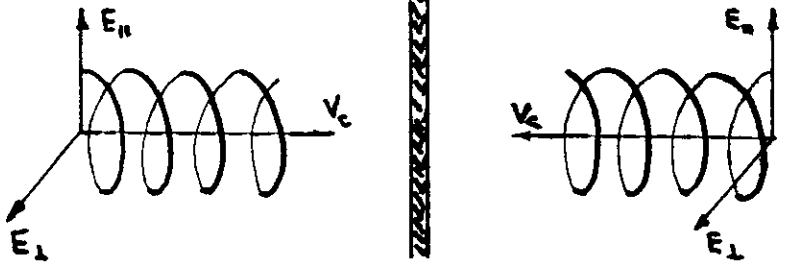
A

B

Multipartical Objects



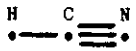
Circular Polarized Light



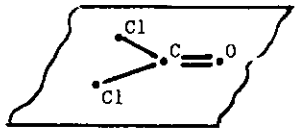
Chiral object has no mirror symmetry and exists it two mirror-conjugated forms

Asymmetric Carbon

Triple bond — HCN — achiral — linear configuration

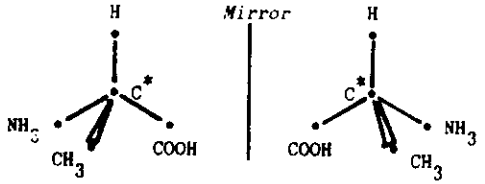


Double bond — Cl_2CO — achiral — flat configuration



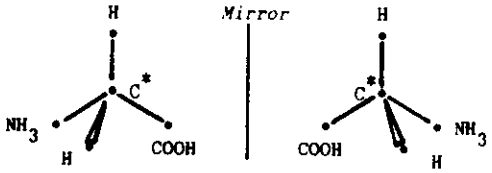
Single bond — Tetrahedral configuration

$NH_3CH_3C^*HCOOH$ — chiral



(L) (D)

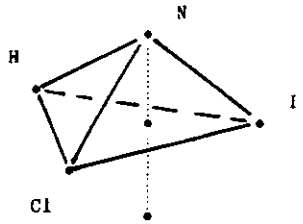
$NH_3HCHCOOH$ — achiral

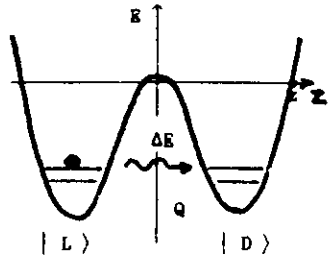


The condition for existence of chiral center C^* :
Four chemical groups bound with carbon should be different

Mirror conjugate forms of chiral molecule are called L and D enantiomers

Chirality and Parity Conservation in Electromagnetic Interactions

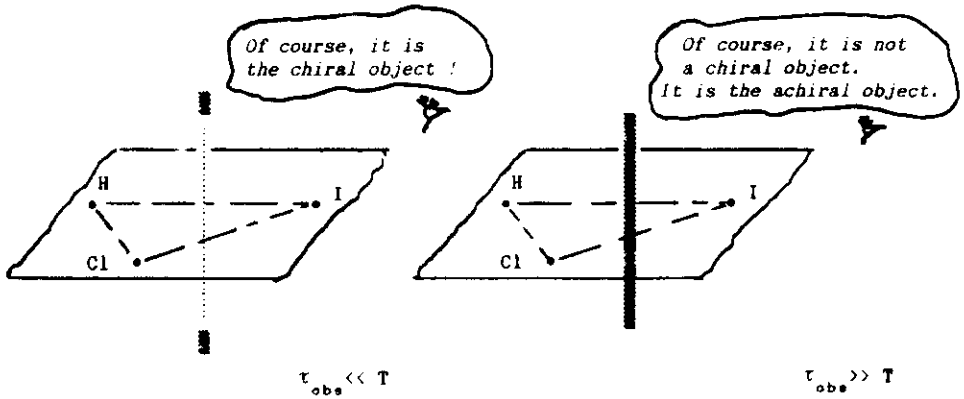




$$| + \rangle = | L \rangle + | D \rangle$$

$$| - \rangle = | L \rangle - | D \rangle$$

$$T = \tau_0 \exp\{(2Em)^{1/2}Q\}$$

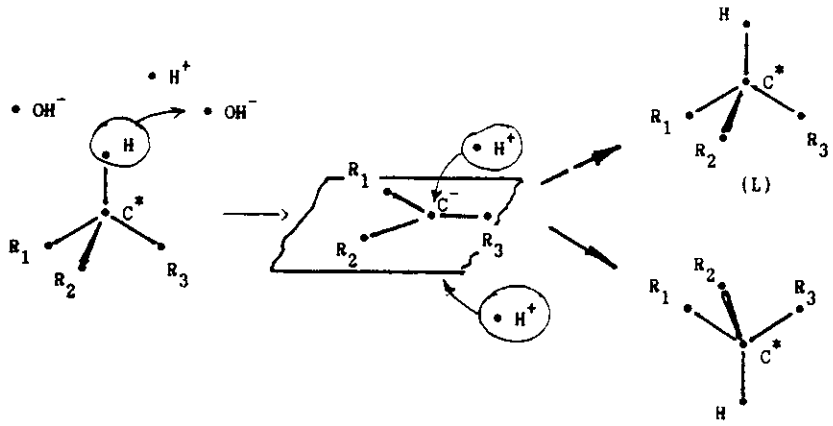


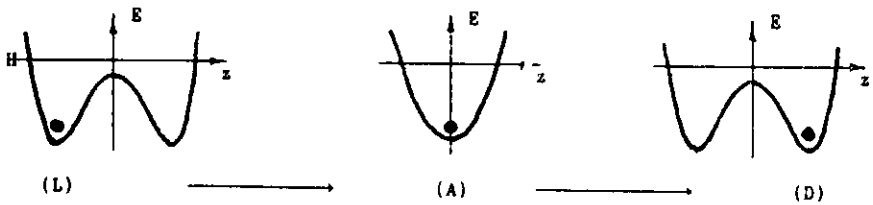
$\tau_{obs} \ll T$ $\qquad$ $\tau_{obs} \gg T$

L and D mirror-conjugated states are observed as steady states on short scale τ_{obs}.

The chiral molecule can be associated with the achiral object on long scale τ_{obs}, for example, in cosmochemical reactions.

RACEMIZATION: INVERSION OF ENANTIOMERS IN CHEMICAL REACTIONS





E is the energy of molecule

z is the reaction coordinate

THE PROCESS OF RACEMIZATION: KINETIC APPROACH

QUANTITIES DESCRIBING SYMMETRICAL PROPERTIES

The chemical system with L and D enantiomers

Chiral polarization :

$\eta = (c_L - c_D)/(c_L + c_D)$

(c_L and c_D are concentrations of L and D enantiomers)

Concentration of chiral product :

$\Theta = c_L + c_D$

Symmetric (so-called racemic) state : $\eta = 0$ ($c_L = c_D$)

Asymmetric state : $0 < |\eta| \leq 1$ ($c_L > c_D$ or $c_L < c_D$)

Chirally pure state : $|\eta| = 1$ ($c_L = 0$ or $c_D = 0$)

THE CHIRAL POLARIZATION CHANGES

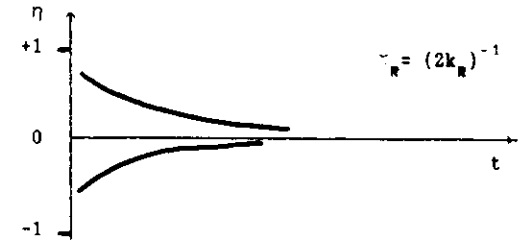
$$L \xrightarrow{k_R} D \qquad D \xrightarrow{k_R} L$$

k_R is the rate constant

$$\frac{dc_L}{dt} = -k_R c_L + k_R c_D \qquad \frac{dc_D}{dt} = k_R c_L - k_R c_D$$

$$\frac{d\eta}{dt} = -2k_R \eta \qquad \frac{d\Theta}{dt} = 0$$

$$\eta = \eta_0 \exp[-2k_R t] \qquad \Theta = \Theta_0$$



The Process of Racemization: Thermodynamic Approach

Thermodynamic potential of ideal solution of L and D enantiomers

$$F = \{ c_L \Phi_L + c_D \Phi_D \} + k_B T \cdot (c_L \ln c_L + c_D \ln c_D)$$

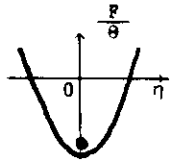
Φ_L and Φ_D are internal energies of L and D isomers, k_B is the Bolzmann constant and T is temperature. In symmetrical environment, for example in achiral solving, $\Phi_L = \Phi_D (= \Phi_0)$.

THE MINIMUM OF THERMODYNAMIC POTENTIAL CORRESPONDS TO THE MAXIMUM OF ENTROPY, NAMELY TO RACEMIC MIXTURE.

$$\min \left(\frac{F}{\Theta} \right) = \Phi_0 + \frac{k_B T}{2} \cdot (\ln \Theta - \ln 2) \quad \text{when} \quad \eta = 0 .$$

In vicinity of racemic state

$$\left(\frac{F}{\Theta} \right) = A_0 + B_0 \cdot \eta^2 \quad , \quad \text{where } A_0 = \left(\frac{F}{\Theta} \right)_{min} \text{ and } B_0 = \frac{k_B T}{2} \quad (>0)$$



If the racemization is the thermodynamic imperative, then the molecular world should be racemic.

What is Biochirality? The First Insight

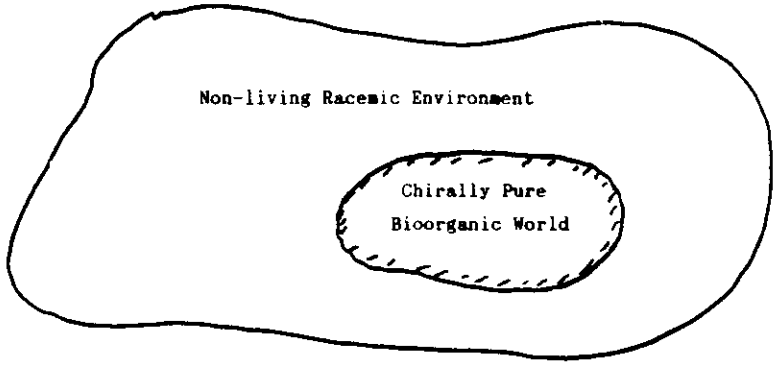
PRACTICALLY ALL BIOLOGICAL OBJECTS CONTAIN ONLY ONE ENANTIOMER OF CHIRAL BIOORGANIC COMPOUNDS.

Classical examples:

All enzymes contain only L-amino acids

All RNA and DNA contain only D-sugars.

THE LIVING MATTER IS CHIRALLY PURE



BIOCHIRALITY IS THE PHENOMENON OF MIRROR SYMMETRY BREAKING IN MOLECULAR WORLD

HYPOTHESIZES

ASYMMETRICAL FORMATION OF ENANTIOMERS:

The influence of weak neutral currents on the formation of chiral molecules stipulated by Bose condensation of atoms to molecule.

ASYMMETRICAL CHEMICAL REACTIONS DUE TO THE INFLUENCE OF ASYMMETRICAL PHYSICAL FACTORS:

chiral minerals (quartz), circular polarized light,
chiral combinations of magnetic, electric and gravitational fields,
polarized product of β-decay ;

PHASE TRANSITIONS:

formation of chirally pure crystals in racemic solutions,
the bifurcation with symmetry breaking in non-equilibrium chemical systems ;

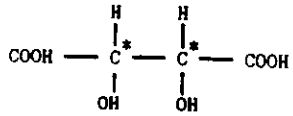
If the physical point of view requires only to show the existence of some natural mechanism for the appearance of asymmetrical molecular world, then this objective is reached today.

The rhetorical question: Many physical causes for mirror symmetry breaking in molecular world exist. However the non-living matter is racemic at the Earth and in cosmic space. Why?

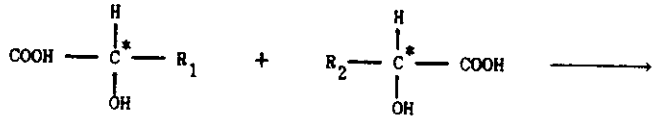
The problem of the Origin of Biochirality is not equivalent to the problem of the formation of asymmetrical molecular world

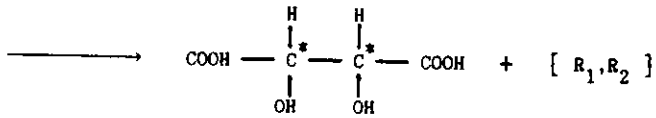
WHAT IS BIOCHIRALITY? MORE DEEP INSIGHT

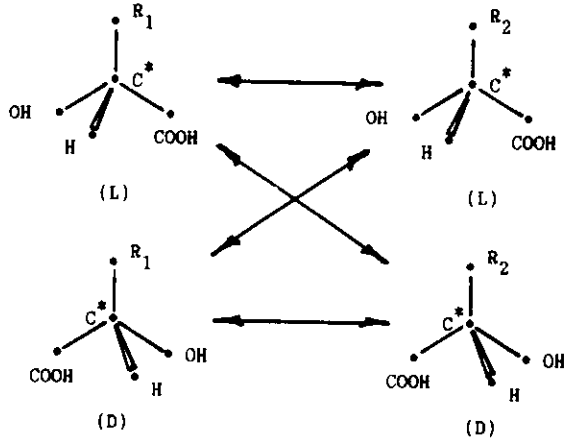
COMPOUNDS WITH TWO CHIRAL CENTERS



Tartaric acid





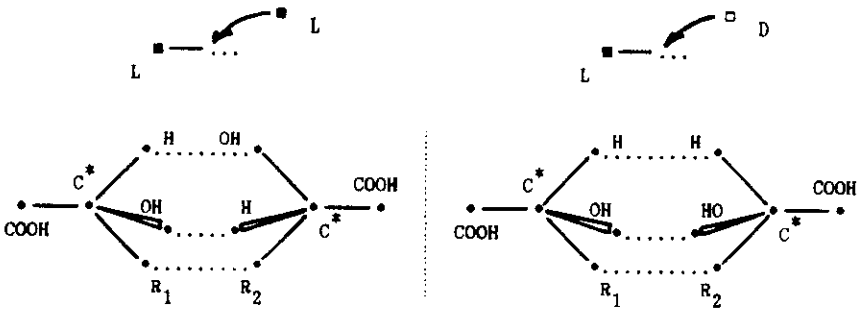


$P = 2^N$

$[\ L_1 - L_2\ ] \overset{\hat{P}}{\longleftrightarrow} [\ D_1 - D_2]$ $\qquad$ $[\ L_1 - D_2\ ] \overset{\hat{P}}{\longleftrightarrow} [\ D_1 - D_2]$

Chiral Discrimination

Intermolecular interactions under the formation of dimer.



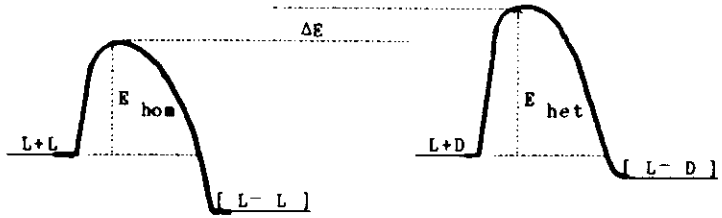
E_{int}^{LL} E_{int}^{DD}

The discrimination energy ΔE is the average over all possible orientations of molecules relative to each other

$$\Delta E = \langle E_{int}^{LL} - E_{int}^{DD} \rangle \propto \begin{cases} (10^{-2} \div 10^{-6}) \langle E_{int} \rangle & \text{in solutions} \\ (10^{0} \div 10^{-2}) \langle E_{int} \rangle & \text{in solids} \end{cases}$$

Enantioselectivity

$$L + L \xrightarrow{k_1} [\, L—L \,] \qquad L + D \xrightarrow{k_2} [\, L—D \,]$$



Barriers of reactions for homochiral and heterochiral dimerizations.

$k_1 = K_0 \exp\{ - E_{hom} / k_B T \}$; $k_2 = K_0 \exp\{ - E_{het} / k_B T \}$

Enantioselectivity can be defined as a relative difference of probabilities of the formation of homo- and heterochiral dimers in racemic environment.

$$\gamma = \frac{(\omega_{hom} - \omega_{het})}{(\omega_{hom} + \omega_{het})} \quad ; \quad \omega_{hom} = k_1^{-1} \, , \; \omega_{het} = k_2^{-1} \quad ; \quad \gamma = \text{th}\left(\frac{\Delta E}{2 k_B T}\right)$$

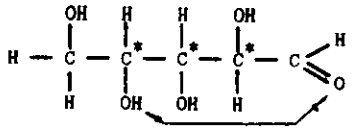
The enantioselectivity γ is less than 10^{-2} in most part of reactions in solutions. For complex compounds with strong limitations for their mobility γ can reach 0.1 ÷ 0.5 .

Bioselection of enantiomers reaches 0.99999999

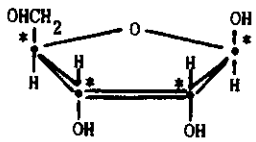
More then Two Chiral Centers: Sugars

Ribose

Linear form

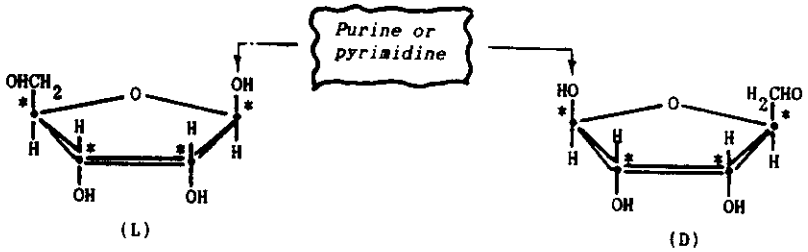


Ring form



4 chiral centers: 2^4 stereoisomers ; 8 different enantiomeric pairs - arabinose, xylose, ribose, lixose and so on.

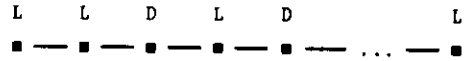
Only two stereoisomers of ribose exist.
They are L and D enantiomers



Only two stereoisomers of ribonucleotides and desoxyribonucleotides exist.
They are L and D enantiomers.

Nucleotides are more complex chiral compounds than amino acids. However this complexity does not lead to fundamental limitations. If the number of chiral centers is less than approx.mately 10, then all possible stereoisomers are accessible for abiogenic synthesis during the chemical evolution.

Chiral Polymers



N units $P = 2^N$ different stereoisomeric forms

The key molecular objects in living systems - DNA, RNA and enzymes - are chiral polymers.

Enzymes contain about of 10^2 - 10^3 chiral centers .

DNA contains up to 10^8 chiral centers .

The key biomolecules are chiral objects with very high degree of complexity.

For N = 400 , P $\approx 10^{130}$ is more than the number of all electrons in the Universe.

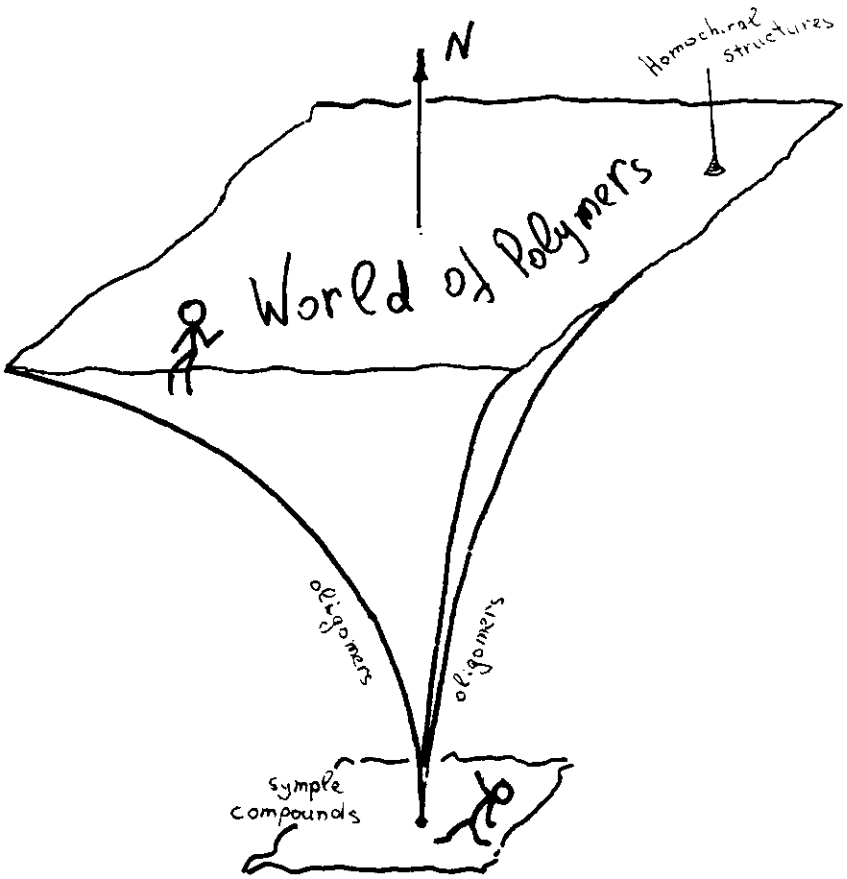
Such a level of complexity leads to the fundamental limitations. If the number of chiral centers is of the order of 10^2 and more, only vanishingly small part of all possible stereoisomers can be realized in Evolution.

The rhetorical question: Nevertheless, this fundamental limitation has not been an obstacle for the origin of Life. Why?

Just such a level of complexity corresponds to the phenomenon of Biochirality: all enzymes contain only L enantiomer of amino acids and all DNA and RNA contain only D enantiomer of nucleotides.

Key biopolymers are homochiral structures.

WHAT IS BIOCHIRALITY?

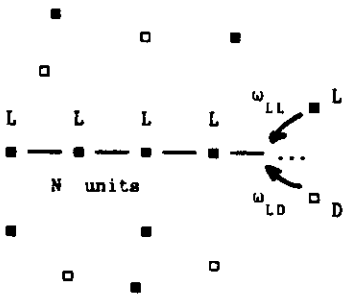


THE PHENOMENON OF BIOCHIRALITY IS, FIRST OF ALL,
THE TAKEOVER OF ORGANIC MEDIUM BY HOMOCHIRAL POLYMERS

THE ORIGIN OF BIOCHIRALITY :
HOW MANY SCENARIOUS CAN BE ?

The Polymeric Takeover by Homochiral Structures

Had this process any general limitations ?



The probability of the formation of homochiral chain depends on both chiral polarization

$\eta = (c_L - c_D)/(c_L + c_D)$

(c_L and c_D are concentrations of L and D enantiomers in the medium) and enantioselectivity

$\gamma = (\omega_{LL} - \omega_{LD})/(\omega_{LL} + \omega_{LD})$

(ω_{LL} and ω_{LD} are relative probabilities of adding the L and D units in racemic environment.

The normalization constant:

$$N_0 = (c_L\omega_{LL} + c_D\omega_{LD})^{-1} = \frac{2}{(1 + \eta\gamma)} \quad .$$

The relative probability of adding L unit:

$$\Omega_L = N_0\, c_L\, \omega_{LL} = \frac{(1 + \eta)(1 + \gamma)}{2(1 + \eta\gamma)} \quad .$$

The relative probability of adding the chiral defect (D unit):

$$\Omega_{def} = 1 - \Omega_L \quad .$$

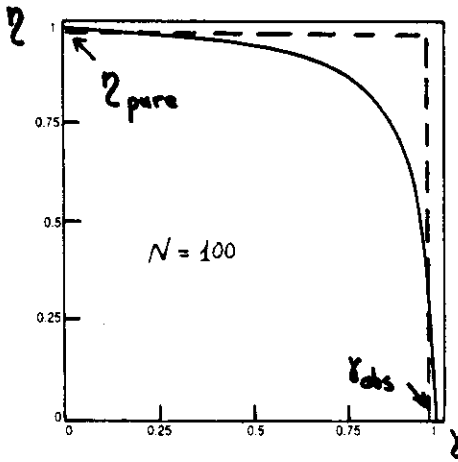
The relative probability of the assembling a of homochiral chain with the length N:

$$\Omega_N = \Omega_L^N = \exp\{ N \cdot \ln(1 - \Omega_{def}) \} \quad .$$

Two Types of Conditions for Polymeric Takeover

The general condition for polymeric takeover:

$$\Omega_N = \exp\{ N \cdot \ln(1 - \Omega_{def}) \} \geq e^{-\alpha} \text{ , where } \max\{\alpha\} \propto 1$$



For $N \gg 1$

$$\eta > \eta_c = 1 - \frac{2\alpha(1 + \gamma)}{1 - \gamma(1 - 2\alpha/N)} \cdot N^{-1}.$$

Approximation for $N \gg 10$.

$$\eta_c(\gamma) = \begin{cases} \eta_{pure}, & \text{if } \gamma < \gamma_{abs} \\ 0, & \text{if } \gamma > \gamma_{abs} \end{cases}$$

where $(1 - \eta_{pure}) \propto N^{-1}$

and $(1 - \gamma_{abs}) \propto N^{-1}$.

The physical meaning of approximation:

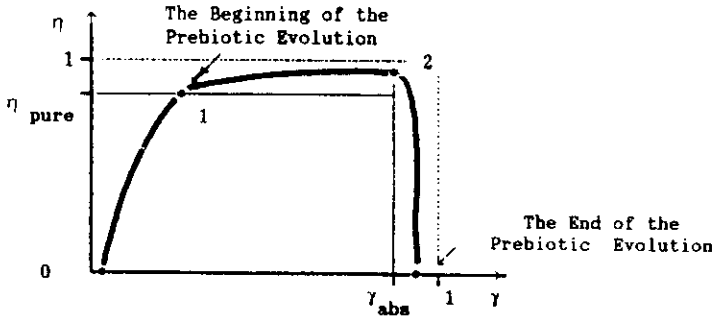
For escape a conflict with so small probabilities as 2^{-100} or $2^{-1000000}$, the total number of chiral defects must be of the order of unity.

1. If enantioselectivity γ is less than γ_{abs} , the polymeric takeover by homochiral chains can be possible only in chirally pure medium ($\eta > \eta_{pure}$).

2. If enantioselectivity γ is more than γ_{abs} , the polymeric takeover by homochiral chains can be possible in any chiral environment

Two Types of Trajectories of Prebiotic Evolution in Terms of Chirality

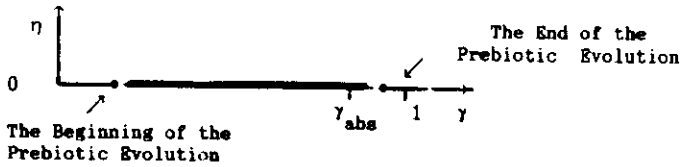
The first type :



The trajectory involves an overcome of two critical points:

1. The appearance of chirally pure organic environment for polymeric takeover.
2. The appearance of the absolute enantioselective polimerization.

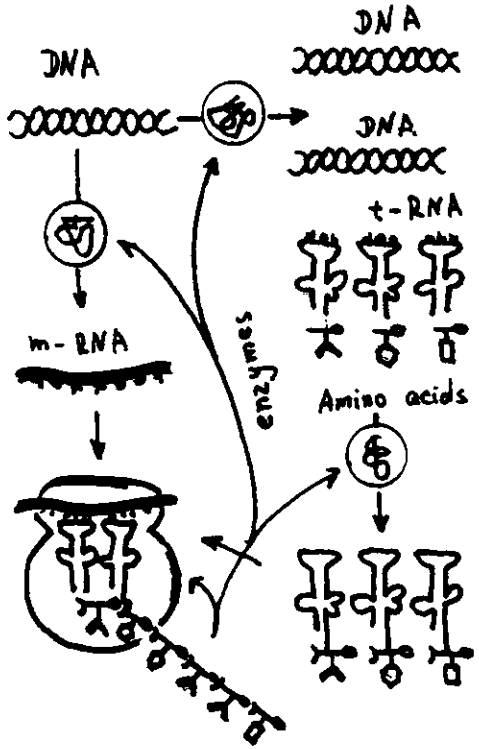
The second type :



The trajectory involves an overcome of one critical point, namely the appearance of the absolute enantioselective polimerization.

What is Attributes of Life ? An Intuitive Definition

The scheme of biological self-replication



The basis patterns of biochemical functions are polymers.

The self-replication is, in some sense, the assembling fixed chains with the length

$N = 10^2 \div 10^6$ units.

The total number of informational sequences

$P = n^N$

for enzymes $n = 20$
for DNA and RNA $n = 4$.

For replication of primary structures of informational chains the total number of mistakes should not be more than unity.

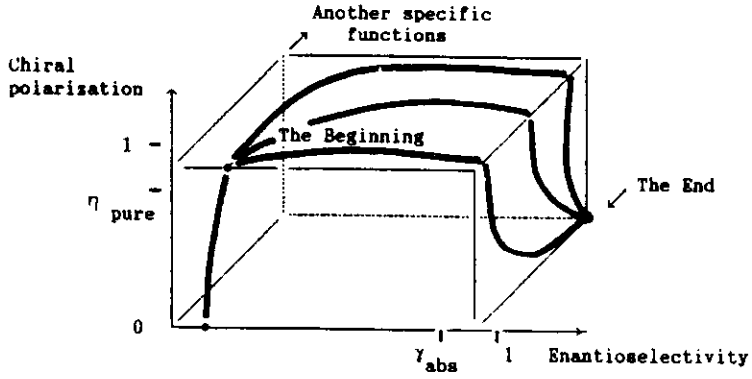
The biological selectivity in the process of self-replication is more than 0.99 and reaches 0.999 999 :

$(1 - \gamma_{biol}) \propto \alpha \cdot N^{-1}$

The absolute enantioselectivity $\gamma_{abs} = (1 - N^{-1})$ is the function of the biochemical level of complexity.

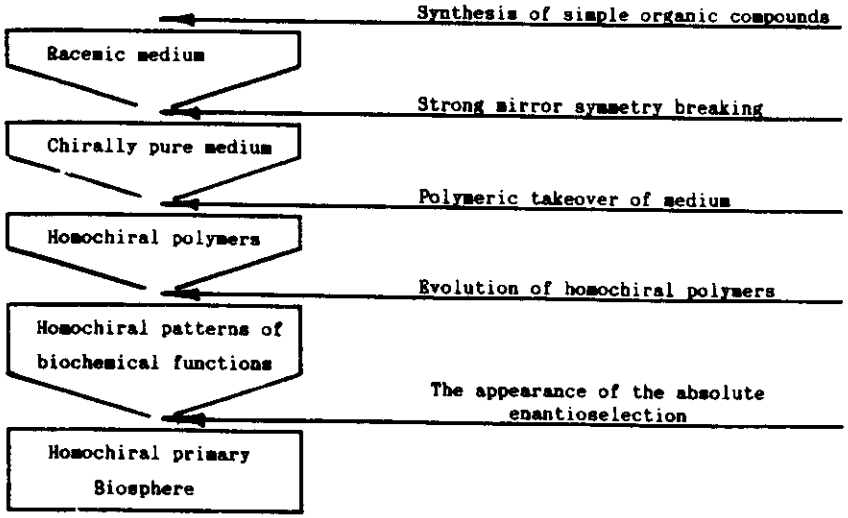
The biological self-replication can be represented in terms of chirality as the absolute enantioselective assembly of polymeric chains.

THE ABIOGENIC SCENARIO FOR THE ORIGIN OF BIOCHIRALITY

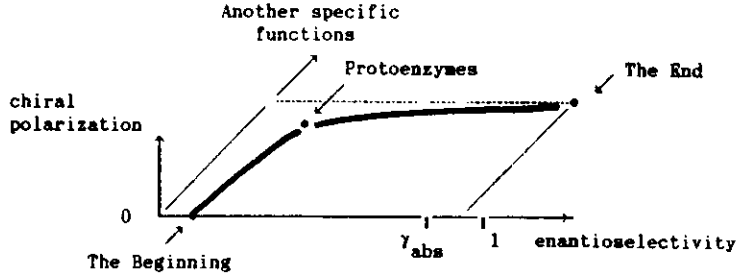


THE EVOLUTION OF STRUCTRURES

THE EVOLUTION OF FUNCTIONS

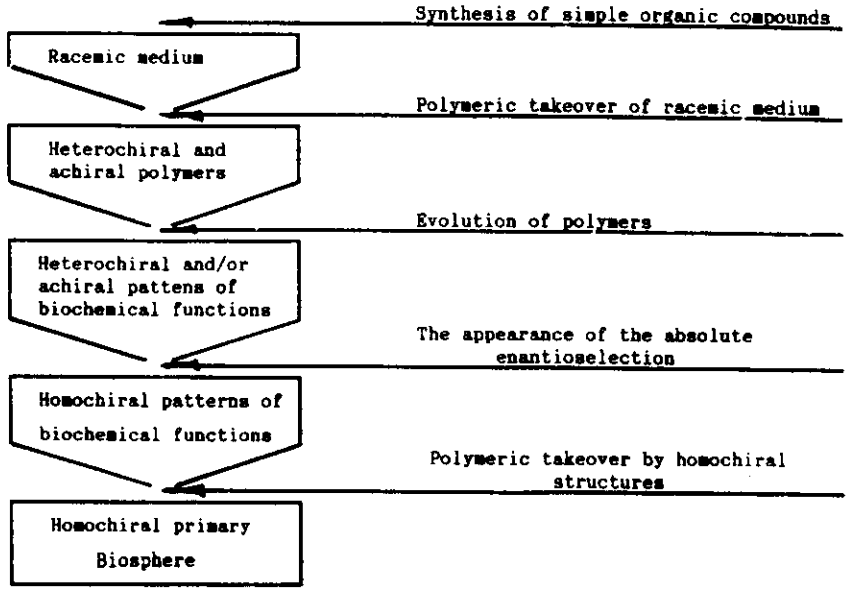


THE BIOGENIC SCENARIO FOR THE ORIGIN OF BIOCHIRALITY



THE EVOLUTION OF STRUCTRURES

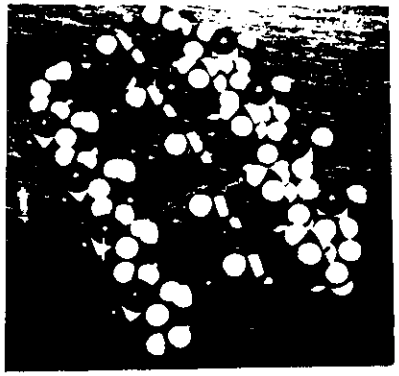
THE EVOLUTION OF FUNCTIONS



Could Heterochiral Protoenzymes with Random Sequences of L and D Units Exist ?

Our approach: The short-range and long-range orders of polymeric units are needed for the formation of enzyme-like patterns

Homochiral chains

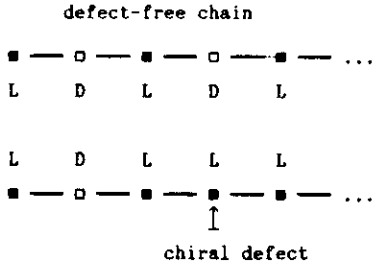


Chains with chiral defect

The appearance of heterochiral protoenzymes with random sequences of L and D units seems to be unlikely due to a strong structural limitation for the formation of short-rang and long-rang orders in compact macromolecules

Could Heterochiral Protoenzymes with Regular Sequences of L and D Units Exist ?

Our approach: The abiogenic conditions for polymeric takeover of racemic medium by unique chiral sequences should exist.



Enantioselectivity:

$$\gamma = (1 - 2\omega_{def}) ,$$

where ω_{def} is the relative probability of adding any chiral defect in racemic environment.

The relative probability of adding L-defect:

$$\omega^{L}_{def} = \frac{(1 + \eta)(1 - \gamma)}{2 (1 + \eta\gamma)}$$

The relative probability of adding D-defect:

$$\omega^{D}_{def} = \frac{(1 - \eta)(1 - \gamma)}{2 (1 + \eta\gamma)}$$

The relative probability of the assembling of a regular heterochiral chain with the length N:

$$\Omega_N = (1 - \omega^{L}_{def})^{N/2} \cdot (1 - \omega^{D}_{def})^{N/2}$$

The general condition for polymeric takeover:

$$\exp \{ \ln(1 - \omega^{L}_{def}) \cdot (1 - \omega^{D}_{def}) \} > - 2\alpha N^{-1} , \quad \text{where} \quad \max \{ \alpha \} < 1 .$$

This condition is fulfilled only for absolute enantioselection:

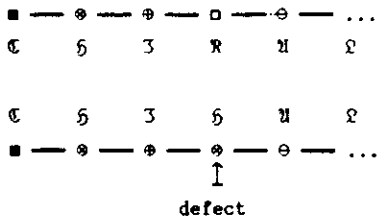
$$\gamma > 1 - 2\alpha \cdot N^{-1}$$

The polymeric takeover by any unique heterochiral chain is exponentially suppressed in abiogenic conditions.

Could Achiral Protoenzymes Exist ?

Our approach: The abiogenic conditions for polymeric takeover of organic medium by unique achiral sequences should exist.

informational chain

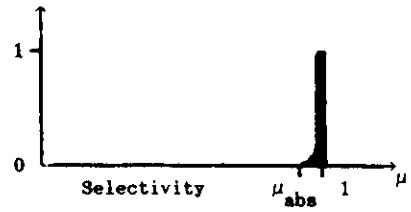


Selectivity of i-type:

$$\mu_i = (1 - 2\omega_{def}^{(i)}) ,$$

where $\omega_{def}^{(i)}$ is the relative probability of adding the defect of i-type in no specific environment.

Specifity of environment



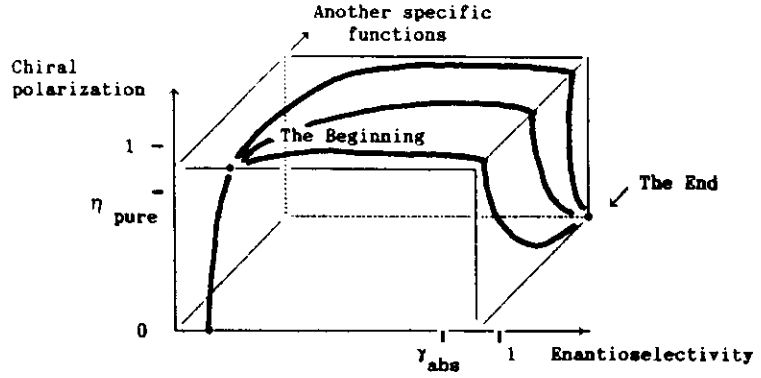
The polymeric takeover by any specific chains in non-specific environment, i.e. the appearance of "informational" polymers, is possible only if the absolute selection exist.

Concluding remarks:

Primary protoenzymes could not appear on the basis of heterochiral and/or achiral polymers, either because of a strong structural limitation for no specific chains or because of strong kinetic limitations for the appearance of any informational structures in the non-specific abiogenic environment.

Biogenic scenario cannot be considered as the basis for the origin of Biochirality.

The Abiogenic Scenario for the Origin of Biochirality



The main requirement:

Chiral purity is necessary not only in the beginning of prebiotic evolution, but had to be maintained in the course of the entire transition to the absolute enantioselection.

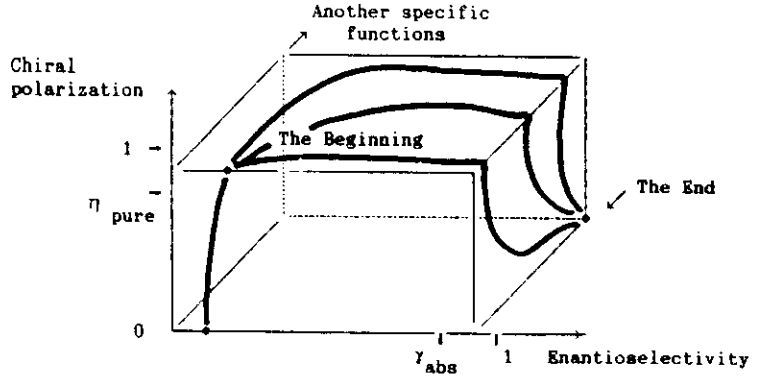
Key questions:

What kind of conditions are necessary for strong mirror symmetry breaking in chiral chemical systems?.

What kind of chemical processes are able to maintain chiral purity during the prebiotic evolution?

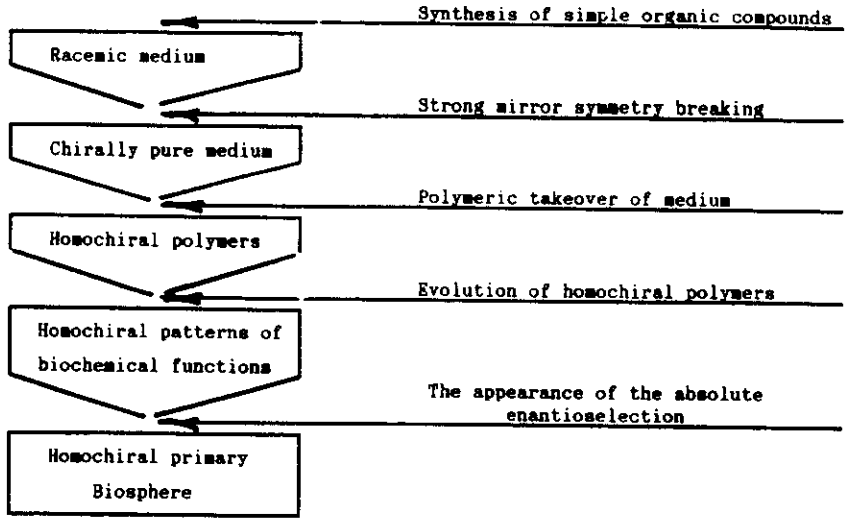
Could Biochirality Result from the Action of Any Asymmetric Forces ?

The Abiogenic Scenario for the Origin of Biochirality



The evolution of structrures

The evolution of functions



The Problem of Strong Mirror Symmetry Breaking

Two key questions:

What kind of chemical processes are capable of strong mirror symmetry breaking?

Are there some of them able to maintain the chiral purity of medium during the period of the formation of the enantioselective function?

Our approach: We must show the very fact of existing of the processes of strong mirror symmetry breaking.

We must show that at least some of them could be stable during the formation of the absolute enantioselection.

Our background: The general theory of mirror symmetry breaking in chiral chemical systems.

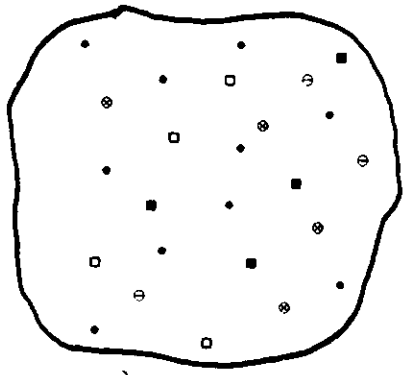
It has been developing in the late 70's and in the early 80's

by L. Morozov, V. Kuz'min, V. Goldanskii and V. Avetisov (on the basis of the kinetic theory of chemical reactions) and

by I. Prigogine, G. Nicolis, D. Kondepudi and G. Nelson (on the basis of methods of the bifurcation theory).

The Mathematical Modelling of Stereochemical Reactions

Chemical system



⊗ ■ } L enantiomers

⊖ □ } D enantiomers

• A (achiral) reactants

Types of transformations:

The formation of chirality

$A \xrightarrow{\{ k_s^L \}} L \qquad A \xrightarrow{\{ k_s^D \}} D$

The inversion of chirality

$D \xrightarrow{\{ k_i^L \}} L \qquad L \xrightarrow{\{ k_i^D \}} D$

The destruction of chirality

$L \xrightarrow{\{ k_d^L \}} A \qquad D \xrightarrow{\{ k_d^D \}} A$

Symmetric conditions : $\{ k_j^L \} = \{ k_j^D \}$, $j = s, i, d$.

Asymmetric conditions: $\{ k_j^L \} \neq \{ k_j^D \}$, for any j.

Kinetic equations:

$$\frac{d\eta}{dt} = f_1\left(k_j^L , k_j^D , c_L , c_D , c_A \right)$$

$$\frac{d\Theta}{dt} = f_2\left(k_j^L , k_j^D , c_L , c_D , c_A \right)$$

The terms on the right-hand side of equations are polynomials in concentrations x_L and x_D of L and D enantiomers.

The Description of Symmetrical Properties of Chiral Chemical Systems

VARIABLES: Chiral polarization :

$$\eta = (c_L - c_D)/(c_L + c_D)$$

(c_L and c_D are concentrations of L and D enantiomers)

Concentration of chiral product :

$$\theta = c_L + c_D$$

EQUATIONS:

$$\frac{d\eta}{dt} = f_1\left(k_j^L , k_j^D , g_j , c_A, \theta, \eta \right)$$

$$\frac{d\theta}{dt} = f_2\left(k_j^L , k_j^D , g_j , c_A, \theta, \eta \right)$$

$g_j = (k_j^L - k_j^D)/(k_j^L + k_j^D)$ is the advantage factor (AF).

For asymmetrical conditions $g_j \neq 0$.

The right-hand side of the equations are polynomials in variables η and θ

WITHOUT ASYMMETRIC FACTOR

$$\frac{d\eta}{dt} = A_1(\theta)\cdot\eta + B_1(\theta)\cdot\eta^3 + \ldots$$

$$\frac{d\theta}{dt} = A_2 + B_2(\eta^2)\cdot\theta + C_2(\eta^2)\cdot\theta^2 + \ldots$$

Only two types of behaviour for chiral polarization are exsist

Processes of the Racemizing Type

THE TYPICAL FORM OF THE EQUATION FOR CHIRAL POLARIZATION UNDER SYMMETRICAL CONDITIONS:

$\frac{d\eta}{dt} = -K_R\eta$, K_R is the half life for racemization.

Examples

THE REACTION OF RACEMIZATION:

$$L \xrightarrow{k^L} D \quad , \quad D \xrightarrow{k^D} L$$

$$\frac{d\eta}{dt} = K\cdot(g - \eta) \; ; \quad \frac{d\theta}{dt} = 0 \; ,$$

$$g = (k^D - k^L)/(k^D + k^L) \; , \quad K = k^L + k^D \; .$$

$$\max\{\eta\} = g$$

THE SIMPLE SYNTHESIS OF ENANTIOMERS:

$$A \xrightarrow{k^L} L \quad , \quad A \xrightarrow{k^D} D$$

$$\frac{d\eta}{dt} = \frac{K\cdot c_A}{2\theta}\cdot(g - \eta) \; ; \quad \frac{d\theta}{dt} = K\cdot c_A \; ,$$

$$g = (k^L - k^D)/(k^L + k^D) \; , \quad K = k^L + k^D \; .$$

$$\max\{\eta\} = g \; .$$

Such processes have no ability for the formation of chirally pure medium.

One Important Example

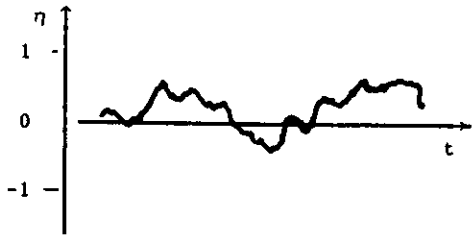
Molecular replication:

The ideal reprcsentation:

$$A + L \xrightarrow{k} L + L \qquad A + D \xrightarrow{k} D + D$$

$$\frac{d\eta}{dt} = 0 \; ; \quad \frac{d\theta}{dt} = K\cdot\theta$$

$$K = k\cdot c_A$$



In reality:

$$A + L \xrightarrow{k_1} L + L \qquad A + D \xrightarrow{k_1} D + D$$

$$A + L \xrightarrow{k_2} D + L \qquad A + D \xrightarrow{k_2} L + D$$

$$\frac{d\eta}{dt} = -K\,(1-\gamma)\,\eta \; ; \qquad \frac{d\theta}{dt} = K\cdot\theta \; ,$$

$$\gamma = (k_1 - k_2)/(k_1 + k_2) \; , \qquad K = (k_1 + k_2)c_A \; .$$

The molecular replication of chiral compounds with out absolute enantioselectivity is the reaction of the racemizing type.

One More Important Example

Destruction of Chirality

$$L \xrightarrow{k^L} A \; , \qquad D \xrightarrow{k^D} A$$

$$\frac{d\eta}{dt} = -Kg\,(1-\eta^2) \; ; \qquad \frac{d\theta}{dt} = -K\cdot(1 - g\eta)\,\theta \; ,$$

$$g = (k^L - k^D)/(k^L + k^D) \; , \quad K = (k^L + k^D)/2 \; .$$

Chiral polarisation increases to 1 (or -1) in asymmetric conditions.

Processes of the racemizing type can amplify an asymmetric forces.

Asymmetric Forces and Strong Mirror Symmetry Breaking

The general form of the equation for racemizing type processes:

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

g is the advantage factor

$\tau = \tau_0^{-1}\cdot t$ is the dimensionless time related to the scale $\tau_0 \propto (k_j^L + k_j^D)^{-1}$,

K_R is the racemizing factor (if $g = 0$, K_R^{-1} is the half life for racemization).

The maximum chiral polarization η_{max}:

$$\eta_{max} = (g/K_R)\cdot\left[1 + \sqrt{1+(g/K_R)^2}\ \right]^{-1} \ .$$

The condition for strong symmetry breaking:

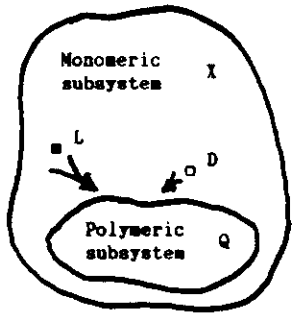
$$\frac{g}{K_R} >> 1$$

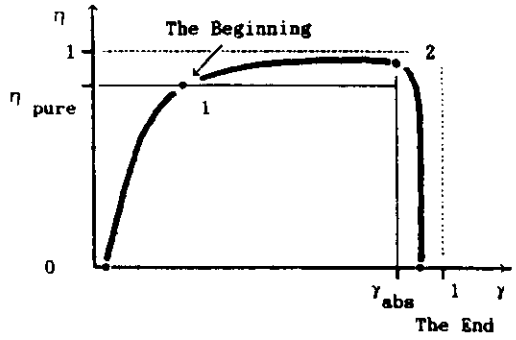
The condition for the beginning of prebiotic transition:

if $\frac{g}{K_R} > N$ ($N > 10^2$), then $\eta_{max} > \eta_{pure}$ ($\eta_{pure} = 1 - N^{-1}$)

If there are no additional requirements, the problem of strong mirror symmetry breaking may be discussed within the framework of the racemizing type processes.

The Model of Prebiotic Evolution in Terms of Chirality





$$\frac{d\eta}{dt} = f_1\left(k_j^L , k_j^D , g_j , c_A, \theta, \eta \right) + \Phi_1(Q)$$

$$\frac{d\theta}{dt} = f_2\left(k_j^L , k_j^D , g_j , c_A, \theta, \eta \right) + \Phi_2(Q)$$

$$\frac{dQ}{dt} = f_3\left(Q , X \right) .$$

Assumptions:

The functions Φ_1 and Φ_2 must describe the flux of enantiomers out subsystem X to subsystem Q .

$$L \xrightarrow{k^L} Q \ , \qquad D \xrightarrow{k^D} Q$$

$$\Phi_1(Q) = - K\gamma (1 - \eta^2) ; \qquad \Phi_2(Q) = - K\cdot(1 - \gamma\eta)\theta \ ,$$

$$g = (k^L - k^D)/(k^L + k^D) \ , \quad K = (k^L + k^D)/2 \ .$$

Evolutionary changes of the polymeric subsystem proceed much slower than chemical transformations in monomeric environment. Therefore we can consider γ as a slowly variable parameter.

Could Biochirality Result from the Action of Any Asymmetric Forces ?

Equations for Evolution on a Thermodynamic Branch:

$$\frac{d\eta}{d\tau} = (g - \tau_0 K \cdot \gamma) (1 - \eta^2) - K_R \cdot \eta$$

$$\frac{d\Theta}{dt} = f_2(X) + \Phi_2(Q) \quad .$$

Enantioselective pressure: $\sigma = \tau_0 K \cdot \gamma$

Enantioselective pressure should increase along the trajectory of the prebiotic transition.

The possible steps:

Synthesis of simple organic compounds

Racemic medium

$K=0 \ , \ (g / K_R) > 10^2$

Amplification of asymmetric forces

Chirally pure medium

$\eta > \eta_{pure}$

Polymeric takeover of medium

Homochiral polymers

$\max \{ \gamma \} \leq g \ (<< \gamma_{abs})$

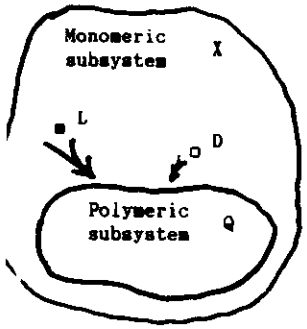
?

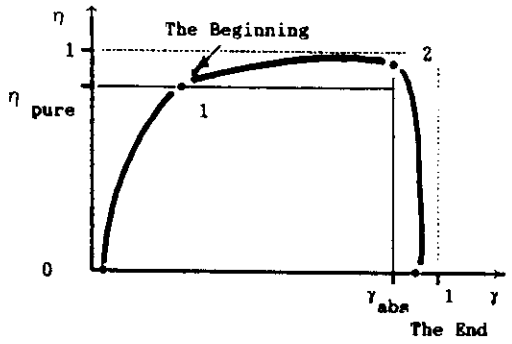
Evolution of homochiral polymers

The transition to self-replicating systems is forbidden on thermodynamic branch of Evolution

The Equation for the Origin of Biochirality

The Model of Prebiotic Evolution in Terms of Chirality





$$\frac{d\eta}{dt} = f_1\left(k_j^L , k_j^D , g_j , c_A , \theta, \eta \right) + \phi_1(Q)$$

$$\frac{d\theta}{dt} = f_2\left(k_j^L , k_j^D , g_j , c_A , \theta, \eta \right) + \phi_2(Q)$$

$$\frac{dQ}{dt} = f_3\left(Q , X \right) .$$

Assumptions:

The functions ϕ_1 and ϕ_2 must describe the flux of enantiomers out subsystem X to subsystem Q .

$$L \xrightarrow{k^L} Q \quad , \qquad D \xrightarrow{k^D} Q$$

$$\phi_1(Q) = - K\gamma (1 - \eta^2) ; \qquad \phi_2(Q) = - K\cdot(1 - \gamma\eta)\theta ,$$

$$g = (k^L - k^D)/(k^L + k^D) , \quad K = (k^L + k^D)/2 .$$

Evolutionary changes of the polymeric subsystem proceed much slower than chemical transformations in monomeric environment. Therefore we can consider γ as a slow variable.

Chemical Processes with the Unstable Racemic State

The simple example:

$$L + L \xrightarrow{k_1} X_{LL} \qquad D + D \xrightarrow{k_1} X_{DD}$$

$$L + D \xrightarrow{1/2\ k_2} X_{LD} \qquad D + L \xrightarrow{1/2\ k_2} X_{DL}$$

$$\frac{d\eta}{d\tau} = - (\gamma\cdot\theta)\cdot\eta + (\gamma\cdot\theta)\cdot\eta^3 ; \qquad \frac{d\theta}{d\tau} = - (1 + \gamma\cdot\eta^2)\cdot\theta^2 .$$

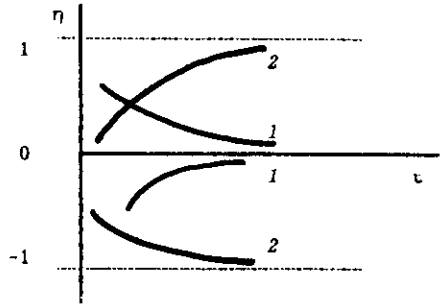
$\tau = 0.5\cdot(k_1 + k_2)\cdot N_A\cdot t$ is the dimensionless time, N_A is the Avagadro number;

$\theta = (c_L + c_D)/N_A$ is the dimentionless concentration of chiral monomers;

$\gamma = \dfrac{(k_1 - k_2)}{(k_1 + k_2)}$ is the enantioselectivity of dimerization.

If $\gamma > 0$, only racemic point $\eta = 0$ is attractive (*1*)

If $\gamma < 0$, only chirally pure points $\eta = \mp 1$ are attractive (*2*)



The mirror symmetry can be broken without asymmetric forces.

AUTOCATALYSIS:

TYPES OF PROCESSES:

Autocatalytic reproduction

$$A + L \longrightarrow L + L \qquad A + D \longrightarrow D + D$$
$$A + L \longrightarrow D + L \qquad A + D \longrightarrow L + D$$

Dimerization

$$L + D \longrightarrow 2\,A$$

$$L + L \longrightarrow 2\,A \qquad D + D \longrightarrow 2\,A$$

The complete scheme of the autocatalytic reaction

$$A + L \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} L + L \qquad A + D \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} D + D$$

$$A + L \underset{k_{-2}}{\overset{k_1}{\rightleftharpoons}} D + L \qquad A + D \underset{k_{-2}}{\overset{k_1}{\rightleftharpoons}} L + D$$

FOR COMPARISON: The classical model of F. Frank for the bifurcation with mirror symmetry breaking.

$$A + L \longrightarrow L + L \qquad A + D \longrightarrow D + D$$

$$L + D \longrightarrow 2\,A$$

The complete scheme of autocatalysis is the modification of classical Frank model without absolute enantioselection.

BIFURCATION WITH MIRROR SYMMETRY BREAKING

THE MODEL OF AUTOCATALYSIS:

Dynamic Equations

$$\frac{d\eta}{d\tau} = \left(2K\gamma_- \cdot \theta + \gamma_+ - 1 \right) \cdot \eta \; - 2K\gamma_- \cdot \theta \cdot \eta^3$$

$$\frac{d\theta}{d\tau} = \theta - \left[2K \cdot (1 - \gamma_-) - 2K\gamma_- \cdot (1 - \eta^2) \right] \cdot \theta^2 ,$$

$\tau = (k_1 + k_2) \cdot c_A \cdot t$ is the dimensionless time,

$\gamma_+ = (k_1 - k_2)/(k_1 + k_2)$ is the enantioselectivity of direct reactions,

$\gamma_- = (k_{-2} - k_{-1})/(k_{-2} + k_{-1})$ is the enantioselectivuty of revers reactions,

$K = (k_{-2} + k_{-1})/(k_1 + k_2)$ is "the measure of non-equalibrium".

The bifurcation equation $$- \eta^3 + \left[\frac{1 - (\gamma_+ + \gamma_-)}{(1 - \gamma_+)(1 - \gamma_-)} \right] \cdot \eta = 0 ,$$

The controlling parameter depends only on enantioselectivity of reactions.

For $(\gamma_+ + \gamma_-) < 1$ only stable steady racemic state exists.

$$\eta = 0 , \qquad \theta = (2K)^{-1}$$

For $(\gamma_+ + \gamma_-) > 1$ three steady states exist, namely unstable racemic state and two stable mirror-conjugated asymmetrical states.

$$\eta_+ = \left[\frac{1 - (\gamma_+ + \gamma_-)}{(1 - \gamma_+)(1 - \gamma_-)} \right]^{1/2} \qquad \eta_- = - \left[\frac{1 - (\gamma_+ + \gamma_-)}{(1 - \gamma_+)(1 - \gamma_-)} \right]^{1/2}$$

$$\theta = \frac{\gamma_+}{K \cdot (1 - \gamma)}$$

In critical point $(\gamma_+ + \gamma_-) = 1$ the racemic state loses the stability and two new symmetrical states bifurcate.

The Critical Enantioselectivity and Complexity of Compounds.

THE CONDITION FOR BIFURCATION WITH SYMMETRY BREAKING IN PROCESSES OF AUTOCATALYTIC TYPE: $\gamma > \gamma_{cr} \approx 0.5$.

THE ENANTIOSELECTIVITY FOR SIMPLE COMPOUNDS: $10^{-4} \div 10^{-2}$

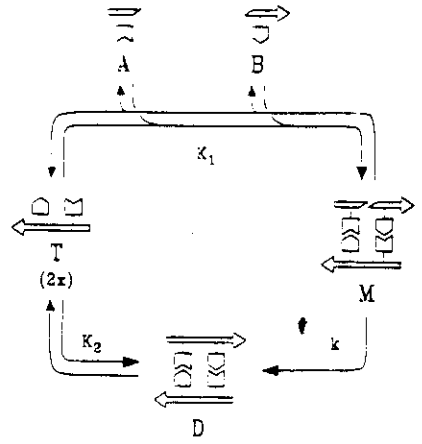
THE ENANTIOSELECTIVITY FOR COMPLEX COMPOUNDS REACHES 0.5

The bifurcation with symmetry breaking can be realized for autocatalysis of sufficiently complex chiral compounds.

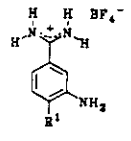
Autocatalysis: Experiments

G.v.Kiedrowski, J.Helbing, S. Jordan, M Matzen, B. Wlotzka

Scheme

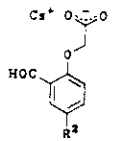


Compounds:



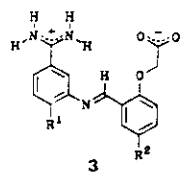
1

a: R^1 = tBu
b: R^1 = Me



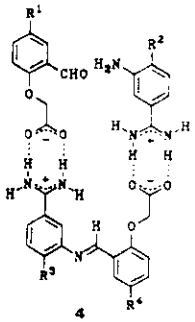
2

a: R^2 = NO_2
b: R^2 = H



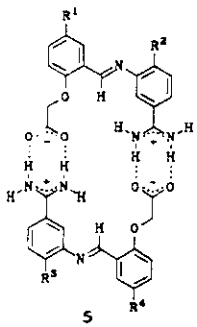
3

a: R^1 = tBu , R^2 = NO_2
b: R^1 = Me, R^2 = NO_2
c: R^1 = tBu , R^2 = H



4

a: R^1 = R^4 = NO_2
R^2 = R^3 = tBu
b: R^1 = NO_2, R^2 = Me
R^3 = tBu , R^4 = H



5

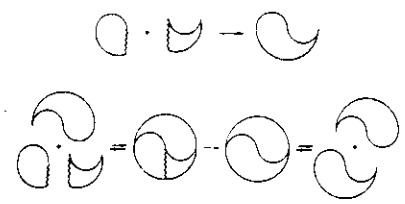
a: R^1 = R^4 = NO_2
R^2 = R^3 = tBu
b: R^1 = NO_2, R^2 = Me
R^3 = tBu , R^4 = H
c: R^1 = R^4 = H

AUTOCATALYSIS: EXPERIMENTS

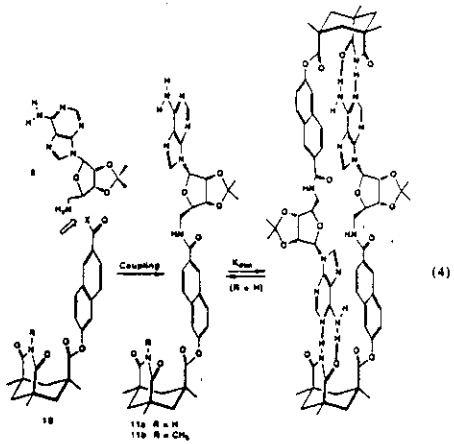
J.Rebek, P.Ballester, T.Tjivikua, Q.Feng, J.Nowick

Scheme

Scheme I



Compounds



(4)

Can such experiments be used as the background of the strong mirror symmetry breaking ?

Chirally pure state can be formed only if γ reaches γ_{abs} .

Therefore one needs more complex processes .

BIFURCATION WITH MIRROR SYMMETRY BREAKING: GENERAL APPROACH.

BIFURCATION EQUATION:

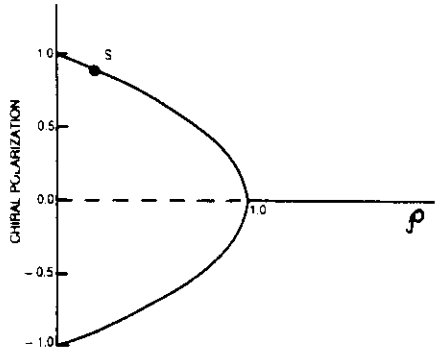
$$\beta \cdot \eta^{\mu} + \alpha \cdot (\lambda - \lambda_c) \cdot \eta = 0$$

In the simplest case $\mu = 3$.

$$- \eta^3 + \left(1 - \frac{1}{\rho} \right) \cdot \eta = 0$$

ρ is the controlling parameter.

BIFURCATION DIAGRAM



The critical point is $\rho_{cr} = 1$.

$0 < \rho < 1$ The only stable racemic state $\eta_0^{(*)} = 0$ exists.

$\rho > 1$ The racemic steady state is unstable.

Two steady states

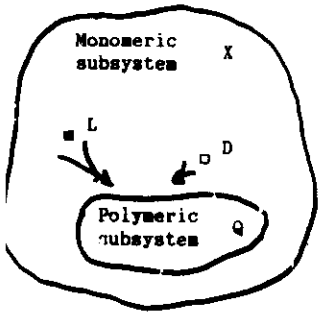
$$\eta_{\pm}^{(*)} = \pm \left(1 - \frac{1}{\rho} \right)^{1/2}$$

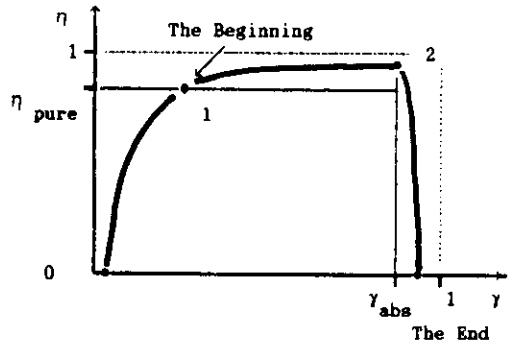
with a broken mirror symmetry are stable

As ρ tends to infinity,

the chiral polarization reaches η_{pure}.

THE EQUATION FOR THE ORIGIN OF BIOCHIRALITY

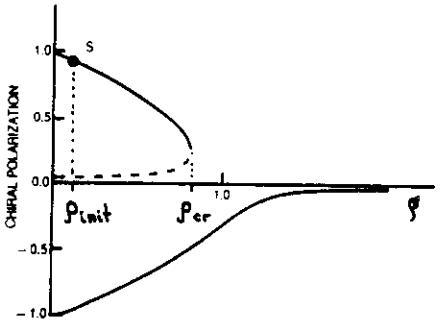




The bifurcation equation under the stereoselective pressure:

$$-\eta^3 + \left(1 - \frac{1}{\rho'}\right)\cdot\eta - \gamma\cdot(1 - \eta^2) = 0 \; ; \qquad \rho' \propto \rho \; .$$

The enantioselective pressure plays the role of an external "chiral field" with the amplitude γ.



For N = 100 :

$\min\{\rho_{init}\} \propto 100$

$(1 - \eta_{pure}) \propto 0.01$

$(1 - \gamma_{abs}) \propto 0.01$

$(1 - \gamma_{cr}) \propto 0.01$

IF THE CHIRALLY PURE MEDIUM HAS BEEN FORMED BY THE BIFURCATION WITH SYMMETRY BREAKING. THE ABIOGENIC TRAJECTORY FOR THE ORIGIN OF BIOCHIRALITY BECOMES OPEN.