Role of Bisolitons and their Correlations in Charge Transfer Processes

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Abstract. The charge transport processes in biological macromolecules are studied within the non-linear electrosoliton mechanism. The interaction between few electrosolitons in a one-dimensional electron-phonon system is investigated. It is shown that in a singlet state the minimum of energy corresponds to a bisoliton. In a triplet state the autolocalized state is described by two electrosolitons which are separated from one another by some finite distance determined by the nonadiabatic terms of the Hamiltonian.

Key words: Bisolitons, charge transport, electrosolitons, respiratory chain

1. Introduction

Many biological processes are connected with the storage and spatial transfer of energy and charge in cells. Davydov [1, 2] has suggested a nonlinear soliton mechanism for the localization and transport of vibrational energy and charges in proteins. According to his hypothesis, the energy stored in the Amid-I vibration of the CO stretching of the peptide group, becomes autolocalized due to the interaction with the local deformation of the relatively soft polypeptide chains formed by weak hydrogen bonds along the α -helical protein molecules. Later on, the bisoliton model of the charge transport in biological systems was proposed [3, 4, 5] according to which electrons are transferred along macromolecules in the form of electrosolitons by the following scheme. An extra electron tunnels from the donor molecule, e.g., NADH molecule, into the prosthetic group on the end of α -helical protein macromolecule, and can be captured by the peptide dipole moment (3.46 D [6]) in a bound state with the binding energy 0.9 eV [7]. The periodical potential of the peptide groups in the α -helix forms the conducting band for electrons [8]. The dipole moment of the peptide group in the presence of an electron changes, which, in its turn, leads to the change of the macromolecule equilibrium configuration. As it was mentioned above, this electron-phonon interaction is essential in the soft polypeptide chains and leads to the autolocalization of the band electron. In the autolocalized state an electron propagates with constant velocity together with the local distortion to the acceptor molecule on the opposite end of the chain, e.g.,

molecular oxygen in the redox processes. The formation of an electrosoliton is described by the system of two coupled nonlinear equations [2, 9].

The metabolic electron transport takes place, for instance, in the respiratory processes in aerobic cells [10, 11, 12]. The respiratory processes consist of three stages: i) the glycolysis, ii) the citric acid (or Krebs) cycle, and iii) the oxidative phosphorylation reactions. The oxidative phosphorylation is the sequence of reactions (the electron transfer chain) in which electrons released from the metabolic products of the Krebs cycle, are transferred through the oxidative-reductive proteins to the molecular oxygen. Until now the study of the role of various enzymes and other proteins in the respiration processes is one of the main problems of biochemistry. The chemical reactions during the glycolysis and the citric acid cycle are well known, while the oxidative phosphorylation processes and role of various electron transmitters participating in these processes are known only in general. The complex enzyme systems form the whole entity with inner mitochondria membrane and function in the form of highly organized macromolecular ensembles. Some components of the electron transfer chain represent protein complexes of enzymes with large molecular masses. These complexes are known to contain subunits of the α -conformation. Particularly in these fragments of the electron transfer chain the formation of electrosolitons is possible during the electron transport from the metabolic substrate to the final electron acceptor (molecular oxygen). The (bi)soliton model for electron transport in biosystems [3, 5] can explain the high efficiency of charge transfer on large distances (the size of the redox ensembles in the inner mitochondria membrane is about 200 Å and an electron passes several times the membrane of the width ~ 50 Å).

Below we consider the main properties of electrosolitons and their interactions in a molecular chain. The relevance of the suggested model to the functioning of the electron transfer chain in the whole is discussed in the last section.

2. Electrosolitons in Molecular Chains

Let us consider a simplified model of an α -helix, namely a polypeptide molecular chain of the length $\mathcal{L} = Na$ (a is the lattice constant, $N \gg 1$). The dipole moments of peptide groups form a periodic potential for an extra electron(s), and, hence, create an electron conducting band. The number of electron levels in such a band and its width are determined by the length of the chain and the overlap of electron wavefunctions on the neighbouring sites (electron exchange interaction, J), respectively. The peptide groups are connected by the hydrogen bonds, and the displacements of the peptide groups from their equilibrium positions can be characterized by the collective vibrational (phonons) modes. Due to the softness of the hydrogen bonds the equilibrium conformation of the chain changes in the presence of extra electron(s), which can be described as the electron-phonon coupling. Therefore, the electron states in such a system can be described by the Fröhlich Hamiltonian

$$\begin{aligned}
H = & \sum_{\sigma,k} E(k) A_{\sigma,k}^+ A_{\sigma,k} + \frac{1}{\sqrt{N}} \sum_{\sigma,k,q} \chi(q) A_{\sigma,k}^+ A_{\sigma,k-q} (b_q + b_{-q}^+) \\
& + \sum_q \hbar \omega_q b_q^+ b_q.
\end{aligned} \tag{2.1}$$

Here $A_{\sigma,k}^+$, $A_{\sigma,k}$ are the Fermi creation and annihilation operators of the electron with spin projection σ and wavenumber k in the conductive band with the dispersion law $E(k)$, b_q^+ , b_q are the Bose creation and annihilation operators of phonons with wavenumber q and frequency ω_q , the value $\chi(q)$ is determined by a short-range interaction of electrons with atom displacements (in a simple chain such displacements correspond to acoustic phonons). In a long-wave approximation, counting the energy from the electron band bottom, one can write

$$E(k) = \frac{\hbar^2 k^2}{2m}, \quad \omega_q = V_a |q|, \quad \chi(q) = i \chi q a \sqrt{\frac{\hbar}{2M\omega_q}} \tag{2.2}$$

where m is the effective mass of an electron in the conductive band, $V_a = a\sqrt{w/M}$ is sound velocity in a chain, w is the elasticity coefficient of the hydrogen bond, and χ is the electron-phonon interaction parameter.

At a moderately strong electron-phonon coupling [13] the adiabatic approximation can be used when studying the Schrödinger equation

$$H|\Psi\rangle = E|\Psi\rangle \tag{2.3}$$

with the Hamiltonian (2.1). It means that the eigenstate vector $|\Psi\rangle$ can be represented in the multiplicative form [14]

$$|\Psi\rangle = |\Psi_{ph}\rangle |\Psi_e\rangle = U(b_q) |\Psi_0\rangle, \quad |\Psi_{ph}\rangle = U|0_{ph}\rangle, \quad |\Psi_0\rangle = |\Psi_e\rangle |0_{ph}\rangle. \tag{2.4}$$

Here the unitary operator

$$U = \exp \left[\frac{1}{\sqrt{N}} \sum_q (\beta_q b_q^+ - \beta_q^* b_q) \right] \tag{2.5}$$

describes the renormalization of the ground state caused by the electron-phonon interaction.

Substituting (2.4) into (2.3) we find

$$\tilde{H}|\Psi_0\rangle = E|\Psi_0\rangle \tag{2.6}$$

where

$$\tilde{H} = U^+ H U$$

$$\begin{aligned}
&= W + \sum_{k,\sigma} \left[E(k) A_{\sigma,k}^+ A_{\sigma,k} + \frac{1}{N} \sum_q \chi(q) (\beta_q + \beta_{-q}^+) A_{\sigma,k}^+ A_{\sigma,k-q} \right] \\
&+ \sum_q \hbar \omega_q b_q^+ b_q + \frac{1}{\sqrt{N}} \sum_{k,q,\sigma} \chi(q) A_{\sigma,k}^+ A_{\sigma,k-q} (b_q + b_{-q}^+) \\
&+ \frac{1}{\sqrt{N}} \sum_q \hbar \omega_q (\beta_q b_q^+ + \beta_q^* b_q), \tag{2.7}
\end{aligned}$$

and

$$W = \frac{1}{N} \sum_q \hbar \omega_q |\beta_q|^2. \tag{2.8}$$

With the help of the unitary transformation [15]

$$A_{\sigma,k} = \sum_i \Psi_i(k) a_{\sigma,i} \tag{2.9}$$

we can introduce new Fermi operators. The coefficients $\Psi_i(k)$ can be chosen from the condition that the part of the operator (2.7) which is quadratic with respect to Fermi operators, is diagonal:

$$E(k) \Psi_i(k) + \frac{1}{N} \sum_q \chi(q) (\beta_q + \beta_{-q}^*) \Psi_i(k - q) = E_i \Psi_i(k). \tag{2.10}$$

This transforms the Hamiltonian (2.7) into the form $\tilde{H} = H_0 + H_1$, where H_0 is the operator which describes the adiabatic states of the electron-phonon system,

$$\begin{aligned}
H_0 &= W + \sum_{i,\sigma} \left[E_i + \frac{1}{\sqrt{N}} \sum_q f_{i,i}(q) (b_q + b_{-q}^+) \right] a_{\sigma,i}^+ a_{\sigma,i} \\
&+ \frac{1}{\sqrt{N}} \sum_q \hbar \omega_q (\beta_q b_q^+ + \beta_q^* b_q) + \sum_q \hbar \omega_q b_q^+ b_q, \tag{2.11}
\end{aligned}$$

and the operator H_1 is the nonadiabaticity operator,

$$H_1 = \frac{1}{\sqrt{N}} \sum_{i \neq i', q} f_{i,i'}(q) a_{\sigma,i}^+ a_{\sigma,i'} (b_q + b_{-q}^+). \tag{2.12}$$

Here

$$f_{i,i'}(q) = \chi(q) \sum_k \Psi_i^*(k) \Psi_{i'}(k - q). \tag{2.13}$$

In the zero order adiabatic approximation neglecting nonadiabaticity operator (2.12) the state vector of N_e electrons in the chain can be written in the general form as

$$|\Psi_0\rangle = \prod_{i\sigma} (a_{\sigma,i}^+)^{n_{i,\sigma}} |0\rangle \quad (2.14)$$

where according to the Fermi statistics $n_{i,\sigma} = 0$ or 1 and $\sum_{i\sigma} n_{i,\sigma} = N_e$. Substituting (2.14) into the Schrödinger equation we get

$$H_0|\Psi_0\rangle = \left\{ W + \sum_{i\sigma} n_{i,\sigma} E_i + \frac{1}{\sqrt{N}} \sum_q \left[\left[\hbar\omega_q \beta_q + \sum_{i\sigma} n_{i,\sigma} f_{i,i}^*(q) \right] b_q^+ + h.c. \right] \right\} |\Psi_0\rangle, \quad (2.15)$$

from where we conclude that the state (2.14) is the eigenstate of (2.11) with the energy

$$E = W + \sum_{i\sigma} n_{i,\sigma} E_i, \quad (2.16)$$

provided the equality fulfills

$$\beta_q = - \sum_{i\sigma} n_{i,\sigma} \frac{f_{i,i}^*(q)}{\hbar\omega_q} = - \frac{\chi^*(q)}{\hbar\omega_q} \sum_{i\sigma k} n_{i,\sigma} \Psi_i^*(k) \Psi_i(k+q). \quad (2.17)$$

We shall look for the solution of Equation (2.10) assuming that $\Psi_i(k)$ are nonzero only at small values of k . In this case we can use the long-wave approximation (2.2) and introduce the functions of the continuous variable x

$$\psi_i(x) = \frac{1}{\sqrt{N}} \sum_k \Psi_i(k) e^{-ikxa}. \quad (2.18)$$

Now Equation (2.10) takes the form

$$-\frac{\hbar^2}{2ma^2} \frac{d^2\psi_i}{dx^2} + U(x)\psi_i = E_i\psi_i, \quad (2.19)$$

and reads as the Schrödinger equation for the electrons in the potential $U(x)$ created by the lattice deformation. Accounting for (2.17) and (2.18), we find

$$U(x) = \frac{1}{N} \sum_q \chi(q) [\beta_q + \beta_{-q}^*] e^{-iqxa} = -\frac{\chi^2}{w} \sum_{i\sigma} n_{i,\sigma} |\psi_i(x)|^2. \quad (2.20)$$

Thus, the self-consistent states of electrons and lattice deformation are governed by a system of many-component nonlinear Schrödinger equations for the occupied states

$$-\frac{\hbar^2}{2ma^2} \frac{d^2\psi_i}{dx^2} - \frac{\chi^2}{w} \left(\sum_{i'\sigma} n_{i',\sigma} |\psi_{i'}(x)|^2 \right) \psi_i = E_i \psi_i. \quad (2.21)$$

Figure 1. The bisoliton charge density distribution.

All excited states can be obtained from the linear Schrödinger equation (2.19) with the given deformation potential $U(x)$. It is remarkable, that in one dimension the system (2.21) has an exact solution for arbitrary number of electrons including one, few [15], and even for finite electron density in a chain, $n_e = N_e/N \neq 0$ at $N \rightarrow \infty$ [16].

In the case of one extra electron in the chain ($N_e = 1$, $n_{1,\uparrow} = 1$, $n_{1,\downarrow} = n_{i,\sigma} = 0$ for $i \neq 1$) there is only one nonlinear Schrödinger equation for the lowest energy level with the well known solution

$$E_1 = -\frac{\hbar^2 \mu_s^2}{2ma^2}, \quad \psi_1(x) = \sqrt{\frac{\mu_s}{2}} \frac{1}{\cosh(\mu_s x)}, \quad \mu_s = g/2. \quad (2.22)$$

Here the parameter g is determined as

$$g = \frac{\chi^2}{2Jw}, \quad J = \frac{\hbar^2}{2ma^2}. \quad (2.23)$$

The total energy (2.16) of the soliton state including the energy of the deformation, is

$$E_S = -\frac{1}{12} J g^2. \quad (2.24)$$

For two electrons in the chain ($N_e = 2$) the ground state corresponds to the occupation of the lowest energy level by two electrons with opposite spins, i.e. $n_{1,\uparrow} = n_{1,\downarrow} = 1$ and $n_{i,\sigma} = 0$, $i \neq 1$. In this case we also have one nonlinear Schrödinger equation which admits the solution (2.22) for which the bisoliton localization parameter and the bisoliton energy are determined as follows:

$$\mu_{BS} = g, \quad E_{BS} = -\frac{1}{3} J g^2. \quad (2.25)$$

Figure 2. The charge density distribution in triplet electron state.

The bisoliton charge density distribution ρ_{bs} proportional to the square of the bisoliton wavefunction is shown in Figure 1.

If the electron spins are polarized in some direction, for example by the external field, they cannot occupy the same level. In this case we have $n_{1,\uparrow} = n_{2,\uparrow} = 1$, $n_{1,\downarrow} = n_{2,\downarrow} = n_{i,\sigma} = 0$, $i \neq 1, 2$. The self-consistent states of electrons obey the two-component nonlinear Schrödinger equations. This system can be solved using the inverse scattering transformation [17] for the two-soliton state, as it was done in [19], or, since it belongs to the Liouville-type class [20], using the method of quadratures, as it was done in [15]. This solution reads as follows

$$\psi_1 = \sqrt{\frac{\mu_1^2 - \mu_2^2}{g}} \frac{\mu_1 \cosh \phi_2}{S}, \quad \psi_2 = \sqrt{\frac{\mu_1^2 - \mu_2^2}{g}} \frac{\mu_2 \sinh \phi_1}{S}, \quad (2.26)$$

where

$$S = \mu_1 \cosh \phi_1 \cosh \phi_2 - \mu_2 \sinh \phi_1 \sinh \phi_2, \quad \phi_1 = \mu_1(x + \lambda),$$

$$\phi_2 = \mu_2(x - \lambda) \quad (2.27)$$

and λ is the constant of integration.

The parameters μ_1 and μ_2 which determine the energies of the bound states, should be found from the normalization conditions

$$\int_{-L/2}^{L/2} \Psi_i^2 dx = 1,$$

and, hence, depend on the length of the chain. At long enough chain the normalization conditions result in $\mu_1 = \mu + \Delta$, $\mu_2 = \mu - \Delta$, where $\mu = \mu_S = g/2$ and $\Delta \sim \exp(-gN/2)$. Then at infinitely small Δ the solution (2.26) describes two electrosolitons separated by the distance

$$R = \frac{1}{2\mu} \ln \frac{2\mu \cosh(2\mu\lambda)}{\Delta} \rightarrow \infty \text{ at } \Delta \rightarrow 0. \quad (2.28)$$

The charge density distribution in such triplet state is shown in Figure 2.

Two electrons in the triplet state have the energy

$$E = -\frac{1}{6}Jg^2 + 2Jg^2 \cosh^2(g\lambda) \exp(-2gR) \quad (2.29)$$

which shows that there is the repulsion between the solitons, caused by the exponentially decreasing force.

From the solution (2.26) it follows that in the long enough chain the two solitons are repelled from one another so that the distance between them exceeds their size (Figure 2). The integration constant λ characterizes the level of the hybridization of electrons in the bound state. At $|\lambda| \geq 5$ the electrons with parallel spins form the uncorrelated state, and their wavefunctions can be described as independent free solitons.

In the case when there are four extra electrons in a chain ($N_e = 4$), the ground state corresponds to the following set of occupation numbers: $n_{1,\sigma} = n_{2,\sigma} = 1$, $\sigma = \uparrow, \downarrow$ and $n_{i,\sigma} = 0$, $i \neq 1, 2$. This leads to the results similar to the one for two electrons in triplet state with the substitution $g \rightarrow G = 2g$. This means that in the zero adiabatic approximation there are two bisolitons with the exponentially decreasing with distance repulsion between them, due to which the bisolitons as well as the solitons in the triplet state, are separated by the distance as maximum as possible for the given chain length.

But the account of the nonadiabatic term H_1 (2.12) of the Hamiltonian results in additional direct interaction between the two solitons or bisolitons via the phonon field which stabilizes the two-(bi)soliton solution. Within the accuracy of the first order perturbation we can write the total energy for the triplet state of two extra electrons in the chain [18],

$$E = -\frac{1}{6}Jg^2 \left(1 + \frac{3\gamma}{8\pi^6 g}\right) + 2Jg^2 \frac{e^{-2gR}}{\cosh^2(\lambda g)} - \frac{3Jg\gamma}{(2\pi)^3 R^2 \cosh(\lambda g)} \left(1 - \frac{1}{3} \cos \frac{2gR}{\pi}\right). \quad (2.30)$$

where γ is the nonadiabaticity parameter:

$$\gamma = \frac{\hbar V_a \pi}{Ja}. \quad (2.31)$$

Therefore, the account of the nonadiabatic corrections leads to the lowering of the total energy of the system. This is given in expression (2.30) by the terms which are proportional to the nonadiabaticity parameter. This lowering of the energy consists of two parts one of which depends on the distance between the solitons c.m.c., R , calculated in the zero adiabatic approximation, and another one is independent of the distance. From Equation (2.30) we conclude that the adiabatic approximation is valid provided the following condition is fulfilled: $3\gamma/8\pi^6 g \ll 1$ and that the

Figure 3. The electron transfer chain in mitochondria. Here S is substrate (e.g., NADH), FP (Fe) is a flavoproteid enzyme, CoQ is a ubiquinon, and Cyt a,b,c are cytochromes.

repulsion between the two (bi)solitons is partly compensated by the interaction between electrosolitons via the phonon field. These results have been obtained from the Hamiltonian (2.1) without the Coulomb repulsion between electrons which is to a great extent screened in the polypeptide chain. In the triplet state the Coulomb repulsion is not essential. It is more actual when studying the singlet states of electrons and can be taken into account phenomenologically [3]: the soliton is spread over few lattice sites, and is stable if the gain of energy due to the binding exceeds the energy of Coulomb repulsion.

Notice that the operator of the total momentum of the system

$$P = \sum_{\sigma,k} \hbar k A_{\sigma,k}^+ A_{\sigma,k} + \sum_q \hbar q b_q^+ b_q \quad (2.32)$$

commutes with the Hamiltonian (2.1) which reflects the global invariancy of the system with respect to the translation transformation by operator $T = \exp(i P \ell / \hbar)$. This means that solitons can propagate along the chain with some finite velocity V which depends on the eigenvalue p of the operator P , $V = dE(p)/dp$. The eigenfunction of the moving soliton can be obtained from (2.4) by the translation transformation T with $\ell = Vt$ [15].

3. Metabolic Transfer of Electrons

The metabolic transfer of electrons takes place in the oxydative system of mitochondria which includes several redox transmitters. The latter form a chain in which each component reduces the next one situated along the chain. Figure 3 shows the generally accepted [10, 11, 12] sequence of the respiratory chain components, i.e., the electron transfer chain.

The transmitters are placed in the inner membrane of the mitochondria and are oriented in such a way that their prosthetic groups can contact each other in the result of some translational, vibrational and rotational motions. The redox potential of the chain components allows the electron flow in one direction [10].

In this scheme the substrate is given by the proton transmitters NADH and FADH₂ which are metabolically reduced in the Krebs cycle, and transfers electrons to the electron transfer chain. The enzyme systems participating in this process, are rather complex and form the whole entity with the cell membrane which functions as the high-organized ensemble. At present only few of them are well studied. First of all these are the compounds with the low molecular weight, like ubiquinon or co-enzyme Q (CoQ), and cytochrome *c*. Co-enzyme Q is the lipid-like compound. The nucleic acid sequence and spatial structure of cytochrome *c* are known. Its poly-

peptide chain does not include the α -helical regions, and the aminoacid residues are in the β -conformation [11]. Other components represent the protein complexes of enzymes with large molecular weight. These complexes contain large subunits in α -conformation [12] and in them the electron transfer in the form of electrosolitons can take place.

The electron-transfer chain shown in Figure 3, can be divided into three parts or complexes connected with one another by low-molecular redox transmitters, ubiquinon and cytochrome *c*. The transmitters represent acceptors for the previous complex and donors for the next one. According to Figure 3, the substrate is the initial donor and oxygen is the last acceptor of electrons. Every part or complex of the electron transfer chain includes ferrum containing enzyme of high molecular weight (flavoproteid or cytochrome) and two low-molecular transmitters which are in contact with opposite prosthetic groups of heavy enzymes. The low-molecular components can easily move in the membrane due to the very low microviscosity (0.9 Pa) of the lipid bilayer. Lateral diffusion coefficients of the cytochrome *c* and CoQ equal $10^{-8} \text{ cm}^2 \text{ s}^{-1}$.

In every complex the low-molecular donor of electrons diffuses into membrane and contacts with the first prosthetic group of the ferrum possessing enzyme. Due to the exchange interaction, $J(R)$ (here R is the effective distance between the donor and ferrum atom of the prosthetic group), electrons can tunnel and pass to the nearest end of the α -helical part of the protein. Here the self-consistent auto-localization of electrons takes place and the electrosoliton formed at the end of the α -helix, moves in the direction of the opposite end with the finite constant velocity. The formation of the soliton at the end of a chain and its motion along the chain was demonstrated in the numerical calculations [21] and studied analytically in [22]. Provided the time of the soliton formation and its escape from the prosthetic group, τ_s , is less than the time of electron return from the prosthetic group to the donor, $\tau_J \approx \hbar/|J(R)|$, $\tau_s \ll \tau_J$, the chemical bond cannot be formed between the donor and the enzyme prosthetic group, and the oxydized donor continues its free diffusion. Upon reaching the opposite prosthetic group of the enzyme, the electron can be transmitted due to the exchange interaction to the acceptor. Since in the soliton state the electron wavefunction is extended over several lattice sites, the electron probability on the end site is nonzero during some time $\delta t > 0$, and this time is enough for the diffusive collision of the mobile low-molecular acceptor with the enzyme. At this stage the irreversible electron tunneling to the acceptor occurs by the electron transfer mechanism of the Förster type with the transfer of the energy access to the surrounding. It means that the inequality should be fulfilled: $\tau_r \ll \tau_J$, τ_{ref} . Here τ_r is the relaxation time connected with the energy dissipation, and τ_{ref} is the time of soliton reflection from the chain end, $\tau_{ref} \approx \tau_s$.

In the respiratory chain there are the following three regions: (i) electron transfer from flavoproteid to CoQ, (ii) electron transfer to cytochrome *c*, (iii) electron transfer from the cytochrome *aa*₃ to the molecular oxygen. It is known that in these three regions the released energy is stored in the form of the trans-membrane

gradient of protons and is used for the synthesis of ATP [10, 11, 12]. The molecular oxygen is the final acceptor of electrons. For the reduction of one oxygen molecule four electrons are necessary. It is still argued whether these electrons are transferred one by one, by pairs, or all together. From the above consideration we can conclude that within the electrosoliton model the electrons can be transferred one by one or by singlet pairs, and between such pairs there is some finite repulsion which does not allow the formation of four-electron drop.

Usually it is assumed that the two-electron transfer takes place in the region NAD-CoQ and the single-electron transfer in the regions which contain cytochromes [10]. Such scheme agrees with the soliton mechanism as it is shown below.

The cytochromes are heme-containing proteins with ferroporphyrine prosthetic groups. In the heme the ferrum atom forms a planar complex with four ligand groups of porphyrine and has the fixed orientation, its fifth and sixth coordination bonds are perpendicular to the porphyrine plane. Moreover, the cytochrome hemes have the fixed orientation. For instance, the prosthetic groups of cytochromes a and a_3 in cytochromeoxidase are perpendicular to the membrane plane [23]. As the result, the magnetic moments of ferrum atoms, $\mu_{Fe} = 2.218\mu_B$, are oriented in one direction and create the magnetic field (here μ_B is the Bohr magneton). This field polarizes electron spins and, hence, in the cytochromes the electrons are transferred in the triplet state. As it was shown above, in the triplet soliton state the electrons are spatially separated.

On the other hand, the flavoproteids contain the so-called non-heme ferrum: their ferrum atoms are not included in the heme group and are in some form without any fixed orientation of the magnetic moments. In this case the average magnetic field is equal zero which favors the formation of singlet bisolitons.

Therefore, the (bi)soliton mechanism of charge transport in biosystems explains the high efficiency of charge transfer on large distances and justifies the hypothesis about the single electron transfer in cytochromes and pairwise electron transfer in flavoproteids [10]. According to this mechanism, the charge transfer processes are sensitive to the microwave electromagnetic radiations (EMR). It is shown in [24, 25] that the EMR has the most profound influence on solitons at two characteristic resonance frequencies. Therefore, the electromagnetic waves of these frequencies should affect the electron transfer processes in mitochondria. One can expect the manifestation of this influence by the change of the respiration rates under the EMR.

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