New mechanism of solution of the $kT$-problem in magnetobiology

Zakirjon Kanokov$^{1,2}$*, Jünn W. P. Schmelzer$^{1,3}$, Avazbek K. Nasirov$^{1,4}$

$^1$Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia

$^2$Faculty of Physics, M. Ulugbek National University of Uzbekistan, Tashkent, Uzbekistan

$^3$Institut für Physik, Universität Rostock, Rostock, Germany and

$^4$Institute of Nuclear Physics, Tashkent, Uzbekistan

(Dated: September 3, 2009)

Abstract

The effect of ultralow-frequency or static magnetic and electric fields on biological processes is of huge interest for researchers due to the resonant change of the intensity of biochemical reactions although the energy in such fields is small in comparison with the characteristic energy $k_B T$ of the chemical reactions. In the present work a simplified model to study the effect of the weak magnetic and electrical fields on fluctuation of the random ionic currents in blood and to solve the $k_B T$ problem in magnetobiology is suggested. The analytic expression for the kinetic energy of the molecules dissolved in certain liquid media is obtained. The values of the magnetic field leading to resonant effects in capillaries are estimated. The numerical estimates showed that the resonant values of the energy of molecular in the capillaries and aorta are different. These estimates prove that under identical conditions a molecule of the aorta gets $10^{-9}$ times less energy than the molecules in blood capillaries. So the capillaries are very sensitive to the resonant effect, with an approach to the resonant value of the magnetic field strength, the average energy of the molecule localized in the capillary is increased by several orders of magnitude as compared to its thermal energy, this value of the energy is sufficient for the deterioration of the chemical bonds.

PACS numbers: 87.15.-v Biomolecules: structure and physical properties 82.35.Lr Physical properties of polymers

*Electronic address: zokirjon@yandex.ru
I. INTRODUCTION

One of key problems magnetobiology is the explanation of the mechanism of influence of weak magnetic fields on biological objects. The experimental data show that influence of weak magnetic fields on the test-system (both of animal [1, 2, 3] and botanical [4, 5] origin) are realized by the same mechanism. As a consequence, similar effects have to be expected to be of significance for human beings as well. A large spectrum of data is known [6, 7], accumulated in biology, biophysics, ecology, and medicine showing that all ranges of the spectrum of electromagnetic radiation may influence health and working ability of people.

The human organs are not capable to feel physically an electromagnetic field surrounding a human’s body; however, it may cause the decrease of immunity and working ability of people, under its influence syndromes of chronic weariness may develop, and the risk of diseases increases. The action of electromagnetic radiation on children, teenagers, pregnant women and persons with weakened health is especially dangerous [6]. The negative influence of electromagnetic fields on human beings and other biological objects is directly proportional to the field intensity and irradiation time. Hereby a negative effect of the electromagnetic field appears already at field strengths equal to 1000 V/m. In particular, the endocrine system, metabolic processes, functioning of head and a spinal cord etc. of people may be affected [6].

The absence of a theoretical explanation of the mechanism of action of weak magnetic fields on biological objects is connected mainly with the so-called $k_BT$ problem. Here $k_B$ is the Boltzmann constant and $T$ is the temperature of the medium. As it is noted in the review [7], at present does not exist a comprehensive understanding from the point of view of physics how weak low-frequency magnetic fields may affect living systems. In particular, it is not clear how low-frequency weak magnetic fields may lead to the resonant change of the rate of biochemical reactions although the impact energy is by ten orders of magnitude less then $k_BT$.

At the same time, up to now there is no theory in the framework of the general physical concepts underlying magnetobiology and heliobiology, i.e. in the field of a science where effects of the weak and super-weak magnetic fields are studied, giving an answer to these questions. There are even no qualitative theoretical models explaining the interaction mechanisms of fields with biological objects. From the point of view of physics, this situation is
connected with complexity of the macroscopic open systems when the concepts of physics, biology, and chemistry are applied. This complexity is caused by the fact that being macroscopic they consist of many different objects being the elements of a structure formation.

In connection with the absence of any standard view on the interaction mechanisms of weak and super-weak external fields with biological systems and, especially with ”a problem \( k_B T \)”, in the papers [8] we proposed a simplified model to study an influence of the weak external magnetic and electric fields on the fluctuation of a stochastic ionic current in blood vessels and leading to a new method of solution of the \( k_B T \) problem in magnetobiology. The present work is written on the basis of results of works [8] extending the analysis performed there.

The aim of the present work is to estimate energy of molecules near to resonant value of a magnetic field.

II. THE LANGEVIN EQUATION AND ITS SOLUTION

A. Basic Equation

More than 90% of biological tissues consists of polar molecules of fibers, nucleinic acids, lipids, fats, carbohydrates and water. The blood of the human being is the multi-component system consisting of plasma and blood cells. As it is known from the physiology of cardiovascular system of people [9], plasma of blood is a water solution of electrolytes, nutrients, metabolites, fibers and vitamins. The electrolytes structure of plasma reminds the sea water that is connected with the evolution of a life form from the sea. Concentrations of ions like \( \text{Na}^+, \text{Ca}^{2+} \) and \( \text{Cl}^- \) in plasma of blood are larger than in cytoplasm. On the contrary, the concentration of ions \( \text{K}^+, \text{Mg}^{2+} \) and phosphate in plasma of blood are lower than one in cells. These facts allow us to consider the blood in blood vessels as a conductor of an ionic electric current.

It is well known that in all conductors the fluctuations of a current take place because of their molecular structure. Such effect has been experimentally measured by Johnson in 1928 and it denoted as the Johnson noise [10]. The spectral density of the Johnson noise does not depend on a frequency and, therefore, it represents the white electric noise. The Johnson noise is observed in the systems being in the equilibrium states or close to them.
The concrete microscopic mechanisms for the occurrence of the Johnson noise can be different. However in all cases the Johnson noise is caused by the chaotic Brownian motion of the charged particles which possesses two important properties: fast casual change of the direction and the basic opportunity of carrying a large charge through the section of a conductor. Thus the geometrical shape of the system considered is of no relevance for the process. The Brownian character of the charge carriers’ motion remains the same. As the Brownian motion of ions is very poorly connected with fluctuations of their number: a disappearance of one particles and a creation of others does not change the essence of the process analyzed. An arbitrarily large number of charge can be transferred by any way through the given section inside of a conductor [11, 12].

This process is stationary, Gaussian and Markovian process. The random ionic current satisfies a linear stochastic differential equation, namely the Langevin equation. An element of the vascular system with a weak random current is assumed to be described as a line element of random current with the length \( L \) located in a weak external static magnetic field \( \vec{B} \). As it is well-known, in this case the acting force onto the element of random current is the force \( F(t) = i(t)LB\sin(\alpha) \), where \( \alpha \) is between directions of the current element \( \vec{L} \) and magnetic field \( \vec{B} \) [13].

In the subsequent analysis we consider the fluctuations of a scalar quantity, the magnitude of the random current. The mentioned circumstances allow us to formulate the basic equations in the following form [8]

\[
\frac{di(t)}{dt} = -\Lambda i(t) + f(t). \tag{1}
\]

Here \( \Lambda = \lambda - \frac{q n_{ch} B}{m} \sin \alpha \), where \( m, q, n_{ch} \) are the mass, charge and number of ions, respectively, in the volume \( V \); \( B \) is the induction of an external magnetic field,

\[
\lambda = \frac{k_B T}{mD} \tag{2}
\]

is the friction coefficient,

\[
D = \frac{k_B T}{6\pi \eta r} \tag{3}
\]

is the diffusion coefficient, \( r \)-ionic radius, \( \eta \) is the viscosity coefficient of liquid;

\[
f(t) = \frac{q}{mL} \sum_i f_i(t), \tag{4}
\]
where \( f_i(t) \) is the random force acting on the corresponding particle. It is the same for any atom of the same type and it is not correlated with the random forces acting on other type ions [12, 14]:

\[
\langle f(t) \rangle = 0, \quad \langle f(t)f(t') \rangle = \gamma \delta(t-t'),
\]

(5)

where

\[
\gamma = \frac{2k_BTq^2n_{ch}\lambda}{mL^2}
\]

(6)
is the intensity of the Langevin source.

**B. Solution of the Basic Equation and General Analysis**

As shown above, the random electric current may be described by the linear stochastic differential equation with white noise as the random source. The process under consideration is a process of Ornstein-Uhlenbeck type and the formal solution of Eq. (1) may be presented in the form [8, 12]

\[
i(t) = e^{-\Lambda t}i(0) + \int_0^t e^{-\Lambda(t-\tau)}f(\tau)d\tau.
\]

(7)
The average value of the current may be determined from Eqs. (5) and (7) as

\[
\langle i(t) \rangle = e^{-\Lambda t} \langle i(0) \rangle.
\]

(8)

One can also easily compute the dispersion of the random current fluctuations, i.e. \( \sigma(t) = \langle i^2(t) \rangle - \langle i(t) \rangle^2 \). This quantity is given by

\[
\sigma(t) = e^{-2\Lambda t} \int_0^t e^{2\Lambda\tau} \gamma d\tau.
\]

(9)

Taking the derivative of Eq. (9) with respect to time, we obtain

\[
\frac{d\sigma(t)}{dt} = -2\Lambda \sigma(t) + \gamma.
\]

(10)
The solution of Eq. (10) with the initial condition \( \sigma(0) = 0 \) has the form

\[
\sigma(t) = \sigma(\infty)(1 - e^{-2\Lambda t}),
\]

(11)

where

\[
\sigma(\infty) = \lim_{t \to \infty} \sigma(t) = \frac{\gamma}{2 \left( \frac{m_{ch} B \sin \alpha}{m} \right)}.
\]

(12)
As evident from Eq. (12), the fluctuations of the random ionic electric current have a resonant character at

$$\lambda = \frac{qn_{ch} B \sin \alpha}{m}. \quad (13)$$

The corresponding magnetic induction $B$ is determined by expression

$$B = \frac{\lambda m}{qn_{ch} \sin \alpha}. \quad (14)$$

### III. RESONANT ENERGY OF MOLECULES

**A. Basic formulas**

For any stochastic process $i(t)$ the power spectrum $i^2(t))$ is defined as a function of the spectral density $S(\omega)$ by the relation [12, 14]

$$\langle i^2(t) \rangle = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) d\omega. \quad (15)$$

For a scalar process with the real part of the relaxation rate $\Lambda$, the spectral density has the following form

$$S(\omega) = \frac{\gamma}{\omega^2 + \Lambda^2}. \quad (16)$$

For the fluctuation of an random ionic current the spectral density is connected with the power $P$ disseminated by the current at the given frequency as

$$P = \frac{1}{\pi} \int_{0}^{\infty} RS(\omega) d\omega, \quad (17)$$

where

$$R = \frac{mL^2 \lambda}{n_{ch} q^2} \quad (18)$$

is the electric resistance of a considered element of current with a length $L$. We substitute (16) in (17) after integrating over $\omega$, we obtain

$$P = \frac{R\gamma}{2\Lambda}. \quad (19)$$

We substitute (18) into (19) and the resulting expression we multiply with the exposition time $t$ then we divide it by the total number of molecules in the considered volume $V$, i.e. $n_{tot} \approx N \cdot V \ (N \approx 10^{28} m^{-3})$. In this way, we obtain the average energy of a molecule [8]

$$\varepsilon = \frac{P t}{n_{tot}} = \frac{k_B T \lambda^2}{n_{tot} \Lambda} t. \quad (20)$$
Because $i(t)$ is a stationary Gaussian process, Eqs. (7) and (11) are sufficient to completely determine the conditional density of probability $P_2$. It is taken from \[12, 14\]

\[
P_2(i(0) \mid i(t), t) = \frac{1}{\sqrt{2\pi\sigma(t)}} \exp \left[ -\frac{(i(t) - i(0) \exp(-\Lambda t))^2}{2\sigma(t)} \right].
\]  

(21)

One can see that the width of the conditional probability distribution depends on $\sigma(t)$ and at the large values of $\sigma(t)$ the density of probability goes to zero.

B. Numerical Estimations

In order to estimate the resonant value of the magnetic induction as described by Eq. (14), we employ the following data \[9\]: for a person of 70 kg weight, we have an amount of 1.7 kg calcium, 0.25 kg potassium, 0.07 kg sodium, 0.042 magnesium, 0.005 kg iron, 0.003 kg zinc. The effect of calcium in the organism of a human being is very significant. Its salts are a permanent constituent of the blood, of the cell and tissue fluids. Calcium is a component part of the cell nucleus and plays a major role in the processes of cell growth. 99% of the calcium is concentrated in the bones, the remaining part in the blood system and tissues.

The blood composes about 8.6% of the mass of a human body. Hereby the fraction of the blood located in the arteries is lower than 10% of its total amount. The same amount of blood is contained in the veins, the remaining 80% are contained in smaller units like the microvasculature, arterioles, venues and capillaries. The typical values of the viscosity of blood plasma of a healthy human being at 37°C are $1.2 \cdot 10^{-3}$ Pa·s \[9\]. The density of the blood is of the order $\rho = (1.06-1.064) \cdot 10^3$ kg/m$^3$ \[9\]. Knowing the radius of the ions, we may determine the diffusion coefficient which is estimated as $D = (1.8-2.0) \cdot 10^{-9}$ m$^2$/s. The friction coefficient is calculated by formula $\lambda = 6\pi\eta r/m$ obtained from formulas (2) and (4). Its value has been obtained: $\lambda = (3-6) \cdot 10^{13}$ s$^{-1}$. For example, for calcium ions we used $r_{Ca} = 10^{-10}$m \[15\], $m_{Ca} = 6.6810^{-26}$ kg and $q_{Ca} = 2 \cdot 1.6 \cdot 10^{-19}$ C and we have obtained $\lambda = 3.52 \cdot 10^{13}$ s$^{-1}$. The aorta can be considered as a canal with a diameter of $(1.6-3.2) \cdot 10^{-2}$ m and a cross section area of $(2.0-3.5) \cdot 10^{-4}$ m$^2$, which splits of step by step into a network of $10^9$ capillaries each of them having a cross section area of about $7.01 \cdot 10^{-12}$ m$^2$ with an average length of about $10^{-3}$ m.

The number of calcium ions in a volume $V=(2-3.5)\cdot10^{-6}$ m$^3$ of the aorta is equal to $n_{ch}=(0.8-1.4)\cdot10^{19}$, in a volume $V = 7 \cdot 10^{-15}$ m$^3$ of the capillary we have $n_{ch} = 2.7 \cdot 10^{10}$. 

7
Substituting these values into Eq. (14), we get, at \( \sin(\alpha) \approx 1 \), for the aorta \( B \approx 0.5 \cdot 10^{-12} \) T and for the capillary \( B \approx 270 \mu T \).

For numerical estimates average energy of a molecule, we express the parameter in the following form

\[ \Lambda = \lambda \left( 1 - \frac{\omega(B)}{\lambda} \right), \quad \text{where} \quad \omega(B) = \frac{q n_{ch}}{m} B. \]  

Substituting into Eq. (20) the values of the total number of molecule in a volume \( V = 7 \cdot 10^{-15} \) m\(^3\) for capillary \( n_{tot} \approx 10^{13} \) and total number of molecule in a volume \( V = (2-3.5) \cdot 10^{-6} \) m\(^3\) for the aorta \( n_{tot} \approx 10^{22} \).

The energy received by a molecule in a capillary during \( t = 1 \) s was calculated for the \( \Lambda = 0.5\lambda, 0.05\lambda, \) and \( 0.005\lambda \) which correspond to values of the induction of an external magnetic field \( B = 135 \mu T, 256.5 \mu T \) and \( 268.65 \mu T \), respectively, because as it was mentioned above \( B = 270 \mu T \) is the resonant value for a capillary. At these values of \( B \) we obtain the following estimates for the energy received by a molecule in a capillary during \( t = 1 \) s: \( \varepsilon \approx 2k_BT, \varepsilon \approx 20k_BT \) and \( \varepsilon \approx 200k_BT \). The similar estimations for the \( \Lambda = 0.5\lambda, 0.05\lambda, \) and \( 0.005\lambda \) for a molecule in the aorta led us to values \( \varepsilon \approx 2 \cdot 10^{-9}k_BT, \varepsilon \approx 20 \cdot 10^{-9}k_BT \) and \( \varepsilon \approx 200 \cdot 10^{-9}k_BT \). Apparently, it follows from these estimates that under identical conditions a molecule of the aorta has \( 10^{-9} \) times less energy than the molecules of capillaries.

At \( \Lambda = 0.5 \cdot 10^{-9}\lambda \) for the molecule of the aorta we get: \( \varepsilon \approx 2k_BT \), but according to Eq. (21) the probability of such a process is close to zero. These estimates show that large vasculatures are more sensitive to ultra-weak field and capillaries are sensitive to weak and moderate magnetic fields.

IV. CONCLUSIONS

The numerical estimations showed that the resonant values of the energy of molecular motion in the capillaries and aorta are different. These estimations proved further that under identical conditions a molecule of the aorta gets \( 10^{-9} \) times less energy than the molecules of the capillaries. The capillaries are very sensitive to the resonant effect, with an approach to the resonant value of the magnetic field strength, the average energy of the molecule localized in the capillary increases by several orders of magnitude as compared to its thermal energy, this value of the energy is sufficient for the deterioration of the chemical bonds. Even if the magnetic field has values not so near to the resonant values, with an
increase of the time of exposition to the magnetic field a significant effect can be reached. A series of experiments are desirable to check the suggested mechanism of an action of the weak magnetic fields on the biological objects, especially, “a $k_B T$ problem”.

Acknowledgments

Authors thank Drs. G. G. Adamian and N. V. Anfonenko for valuable discussions and comments. Z. Kanokov is grateful to the Deutsche Forschungsgemeinschaft (DFG 436 RUS 113/705/0-3) for the financial support.

[1] W.E. Koch, B.A. Koch, A.N. Martin, G.C. Moses, Comp., Biochem. Physiol., A 105, 617 (1993).
[2] J. Harland, S. Eugstrom, R. Liburdy, Cell Biochem. Biophys., V. 31, No 3., 295 (1999).
[3] G. C. Moses, A. H. Martin, Biochem. Mol. Biol. International., 29, 757 (1993).
[4] F. Bersani (Ed.), Electricity and Magnetism in Biology and Medicine (Kluwer, Acad./Plenum Publ., New York, 1999).
[5] V. V. Lednev, Biophysics, 41, No. 1, 224 (1996); V.V. Lednev, L. K. Srebnitskaya, E. N. Ilyasova, Z. E. Rozhdestvenskaya, A. A. Klimov, N.A. Belova, Kh. P. Tipas, Biophysics, 41, No. 4, 815 (1996); V.V. Lednev, L. K. Srebnitskaya, E. N. Ilyasova, Z. E. Rozhdestvenskaya, A. A. Klimov, Kh. P. Tipas, Doklady Akademii Nauk SSSR, 348, No. 6, 830 (1996).
[6] N. G. Ptitsyna, G. Villoresi, L. I. Dorman, N. Lucci, M.I. Tyasto Physics-Uspekhi, 41, 687 (1998). N.G. Ptitsyna a, G. Villoresi b, L.I. Dorman c, N. Iucci d, a
[7] V. N. Binhi and A. V. Savin, Physics-Uspekhi, 46, 259 (2003); V. N. Binhi, A. B. Rubin, Electromagn. Biol. Med. 26, 45 (2007).
[8] Zakirjon Kanokov, Jurn W. P. Schmelzer, Avazbek K. Nasirov arXiv:0904.1198v1; arXiv:0905.2669v1.
[9] D. Marmon, L. Heller, Phisiologiya serdechno-sosudistoy sistemy (Izdatelstvo "Piter", S.Petersburg, 2002) (In Russian); Yu. N. Kukushkin, Khimiya vokrug nas (Vysshaya shkola, Moscow, 1992) (In Russian).
[10] J. B. Johnson, Phys. Rev. 32, 97 (1928).
[11] G.N. Bochkov, Yu.E. Kuzovlev, Uspehi Phys. Nauk. 141, 151 (1983) (In Russian).

[12] J. Keizer, Statistical Thermodynamics of Non-Equilibrium Processes (Springer, Berlin, 1987).

[13] Edward M. Purcell, Electricity and magnetism. Berkeley physics course., V.2 (Mcgraw-hill book company, 1984).

[14] N.G. van Kampen, Stochastic Processes in Physics and Chemistry (North-Holland, Amsterdam, 1981).

[15] R. D. Shannon, Acta Cryst. A 32, 751 (1976).