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Physical properties of biophotons and their biological functions

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Biophotons (BPHs) are weak photons within or emitted from living organisms. The intensities of BPHs range from a few to several hundred photons· s^{-1}·cm^{-2}. BPH emission originates from a de-localized coherent electromagnetic field within the living organisms and is regulated by the field. In this paper based on the experimental results of Poisson and sub-Poisson distributions of photocount statistics, the coherent properties of BPHs and their functions in cell communication are described. Discussions are made on functions which BPHs may play in DNA and proteins functioning including the process of DNA replication, protein synthesis and cell signalling and in oxidative phosporylation and photosynthesis.

Keywords: Biological regulation, Biophotons, Cell communication, Coherent state, Squeezed state

The weak light emission from living organisms also called ultra-weak bio-luminescence was discovered by Russian scientist Gurwitsch in 20's of the last century. He used two small onion rootlets; one was used as the inductor and placed flatly, and the other was used as detector and was perpendicularly placed close to the inductor's root tip where cell division was copious. Gurwitsch found that the rate of cell division in the detector stem that was pointing towards the tip of the inductor increased when the detector was covered by a quartz glass tube, but the rate did not change if covered with a normal glass tube. He explained that the UV light which can pass through the quartz glass and emitted from the inductor tip induced cell division. Gurwitsch termed this radiation as "mitogenetic radiation" and afterward he found this radiation in many other biological organisms. Since then many scientists in Russia, Poland, Japan, United States, Australia, Germany and China have been investigating weak emission in widely divergent biological systems using photomultipliers. Up to now it has been confirmed that biophoton (BPH) emission exists not only in UV band but also in visual and may exist in infrared bands. However there are two different explanations for their origins and functions. One explanation is that photons are occasionally emitted when living systems fall back into thermal equilibrium from excited states and highly reactive substances such as free radicals can be the most likely source of photons. The other explanation is by a German biophysicist F. A. Popp who starting in the beginning of 70's of last century, investigated BPH emission systematically and put forward that BPH emission originates from de-localized coherent electromagnetic field within the living organisms [1,2]., BPHs are regulated by the coherent electromagnetic field and the BPH field is the regulator for the livings at the same time. The author cooperates with Professor Popp in BPH studies since 1993. While in the first part of this paper experimental results are taken to explain properties and functions, in the second part regulating roles which BPHs may play in answering some problems appearing at present time are discussed.

Physical property of biophotons

The major characteristic of BPHs based on experimental reports and as summarized by Popp[2] are the following: (i) Nonlinear property, (ii) Low radiation strength, (iii) Spectral distribution of strength I (ν) is rather flat without special peaks, (iv) The delayed luminescence decays very slowly, and the dynamic process of the relaxation does not follow the exponential decay but matches to the hyperbolic decay, (v) The probability of recording n photons within Δt time follows Poisson distribution, and (vi) BPH emission is extremely sensitive to environments.

Galle *et al*[3] reported that intensity of photon emission from a sample containing *Daphnia* did not increase linearly with increasing density of *Daphnia*, but displayed rather an interference-like pattern. The minima and maxima can be assigned to definite mean

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values of their mutual distances among *Daphnia*[3]. Schamhart *et al.*[4] and Scholz *et al*[5] observed significant difference in delayed luminescence between tumor and normal cells after illuminating the suspended cultured cells with visual light for 5 min. With increasing cell density, the intensity of delayed luminescence increases for tumor cells, but decreases for normal cells after a certain density[4,5]. Popp and Li[6] claimed that hyperbolic decay of delayed luminescence is a necessary and sufficient condition for the coherent state. During the decay process oscillations were observed that were considered as the results of coupling of at least two modes of coherent state [7].

Photon statistics giving distribution of probabilities of measuring n photons (n= 0,1,2,…) in a given time interval of $\Delta\tau$, $P(n\ \Delta\tau)$ is significant for studying properties of photon fields and the coincidence counting system (CCS) is a good method for studying photon statistics. The principle of CCS method is the following[8]. Channel 1 and channel 2 are registering channels which can separately register photons by two photomultipliers. In the CCS there is the third channel, the coincidence channel which is a counting device. If channel 1 is set as the counting channel then the channel 2 is the reference one (Fig. 1). During the measuring time Δt, as soon as at least one single photon is registered in the channel 1, the gate of the coincidence channel is opened with a small time delay τ and kept opened for a time interval $\Delta\tau$ during which the photons in the channel 2 are registered as the coincidence photon with those in the channel 1. The parameters τ , $\Delta\tau$ and Δt and the setting of the counting channel can be chosen before measuring. Using CCS the registered random coincident photon number is:

$$Z = n_2 P_1(n_1 \geq 1) \quad \ldots(1)$$

where P_1 is the probability of recording n_1 photons ($n_1 \geq 1$) in the counting channel. Z and n_2 is the photon numbers registered in the coincidence and the reference channel respectively. Since Z , n_1 and n_2 are given from measurements , P_1 ($n_1 \geq 1$) and $P(0)$ can be measured.

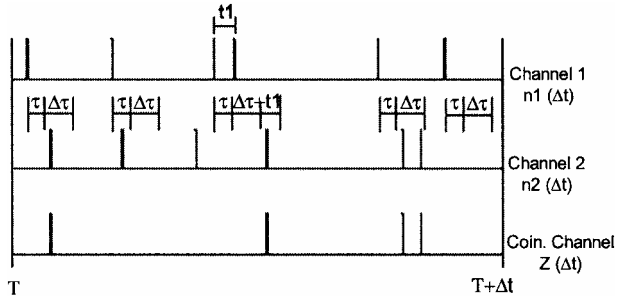

Fig. 1—The principle of coincidence counting system

Theoretically the distributions of P ($n \geq 1$) and $P(0)$ for different states of photon field with an average photon number of $\langle n \rangle$ are formulated differently[9]:

$$P(n) = \frac{\langle n \rangle^n}{(\langle n \rangle + 1)^{n+1}} \quad \text{for chaotic state,} \quad \ldots (2)$$

$$P(n) = \exp(-\langle n \rangle) \cdot \frac{\langle n \rangle^n}{n!} \quad \text{for coherent state,} \quad \ldots (3)$$

for a fully coherent field, $P(n, \Delta\tau)$ follows Poisson distribution and does not depend on $\Delta\tau$ but for a chaotic field if $\Delta\tau << T$ which is the coherent time of this field follows geometric distribution, if $\Delta\tau >> T$, $P(n, \Delta\tau)$follows Poisson distribution also. When n =0,

$$P(0) = \frac{1}{(\langle n \rangle + 1)} \quad \text{for chaotic state,} \quad \ldots (4)$$

$$P(0) = \exp\langle -\langle n \rangle \rangle \quad \text{for coherent state,} \quad \ldots (5)$$

$$P(0) = \left(\frac{1 + \tanh r}{\cosh r}\right) \cdot \exp(-\langle n \rangle \exp(2r)) \quad \text{for squeezed state.} \quad \ldots (6)$$

Here r is the squeezed factor, if r =0, then

$$P(0) = \exp\langle -\langle n \rangle \rangle \quad \ldots (7)$$

Comparing measured results with theoretical curves one can find the property of BPH field under study. In our CCS experimental studies different materials including dinoflagellates, brains of chick embryos and fireflies (Table 1) were used as the test samples and different measuring parameters (Table 2) were tested. In some experiments (Figs 2-4) two samples were placed separately in the two chambers registered by the two registering channels. In some experiments one sample (Fig. 5) was used which was placed in one chamber or between the two chambers. The experimental results show that distributions of photocount statistics match to Poisson curve and not geometric curve as shown in the Figs. 2, 4 and 5 where unfilled circles are measured results, the solid line is the expected theoretical Poisson curve and the dashed line (the lower curve) is the expected geometric curve. Some experimental results follow

super-Poisson and sub-Poisson distribution as shown in Fig. 3 where the solid line (the lower) is the expected theoretical Poisson curve, the dashed line is the geometric curve.

The photocount statistics following Poisson distribution and the delayed luminescence displaying hyperbolic decay are necessary and sufficient conditions for a coherent field. The photocount statistics following sub-Poisson is the sufficient condition for squeezed states. Living organisms emitting squeezed light was reported for the first time by Popp and Chang *et al*[9, 10].

Table 1—Materials measured by CCS method

Materia	Referance
Dinofllagellates *Gonyaulax polyedra*	Popp [1]
Dinofllagellates *P.elegans*	Chang *et al*, *Acta biophsica* 10 (1994) 641 (in Chinese)
Isolated brain of chicken embryos	Chang *et al*, *Science in China*, *C*, 40(1997) 43
Fireflies *(Lampyridea*)	Chang *et al* in Biophotonics and Coherent System edited by Beloussov *et al* (2000) 267
Tomato seedlings	
Bacteria	
Wheat seeds	
Micro lamps (as controls)	

Table 2—Parameters used in the CCS measurements

Terms	Range and conditions
Present measuring time Δt	10^{-2}s, 10^{-1}s, 1s, 10s, 60s
Delay time τ	0 (minimum $\approx 10^{-7}$), 10^{-5}, 10^{-4}, 10^{-3}, ··· but $<\Delta\tau$
Coincidence time interval $\Delta\tau$	10^{-5},10^{-4},10^{-3}, ··· but$>\tau$ and$<$ reversal of counts/s

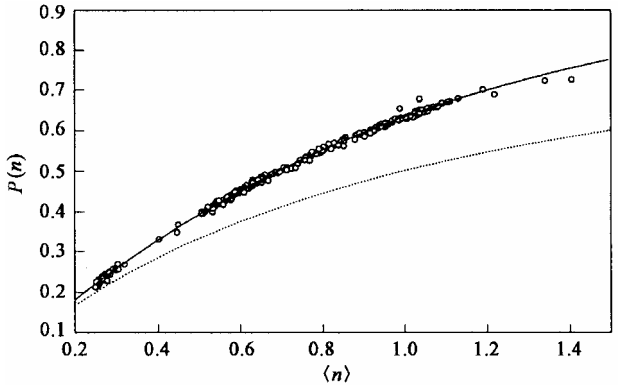

Fig. 2—Measured $P(n)$ from *Denoflagellate eleganece* (measured parameters: Δt=1s, $\Delta\tau = 3\times10^{-4}$s, $\tau \cong 10^{-7}$s)

Functions of biophoton fields

The coherent and squeezed coherent states have significant advantage in communication. According to Heisenberg's uncertainty principle, if microscopic variables are measured by macroscopic quantities, because of the duality of microscopic particles, any two conjugate physical variables, for instance, position q and momentum p, energy E and time t, etc., can not be measured precisely and simultaneously. The product of the uncertainties of any two conjugate

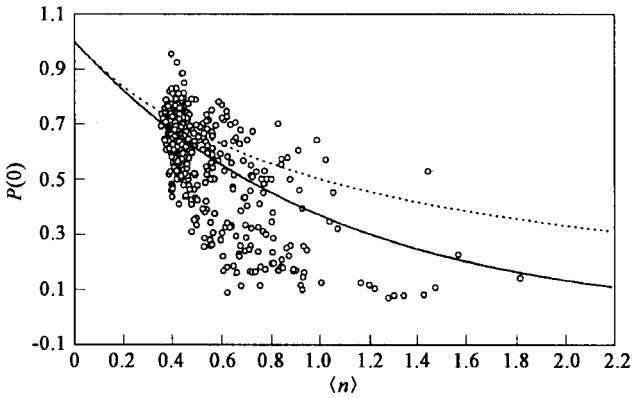

Fig. 3—Measured P(o) from *Denoflagellate gonyaulax (*measured parameters: Δt=1s, $\Delta\tau = 3\times10^{-3}$s, $\tau = 10^{-5}$s

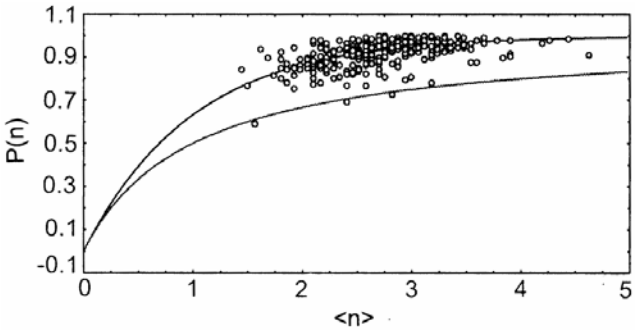

Fig. 4—Measured P(n) from brains of chicken embryos (measured parameters: Δt=1s, $\Delta\tau = 6\times10^{-2}$s, $\tau \cong 10^{-7}$s.)

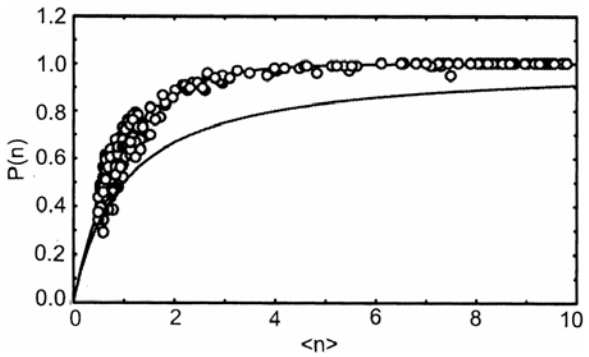

Fig. 5—Measured $P(n)$ from *Denoflagellate eleganece* (measured parameters: Δt=1s, $\Delta\tau = 10^{-3}$ s, $\tau \cong 10^{-7}$s.)

physical variables, for instance $\Delta p \cdot \Delta q$, $\Delta E \cdot \Delta t$, has a limitation of $\geq \eta /2$, where $\eta = h / 2\pi$, h is plank constant $=6.627\times10^{-27}$erg· sec (6.627×10^{-34}J· sec). The uncertainty relation is also written as $\Delta X_1 \cdot \Delta X_2 \geq 1$ for a model of two quadratures of electromagnetic field. The coherent or squeezed coherent state is the state where the uncertainties are in the minimum showed by the curve $\Delta X_1 \cdot \Delta X_2 = 1$ (Fig. 6). On this curve the special point of $\Delta X_1 = \Delta X_2 = 1$ corresponds to the coherent state and the others to the squeezed coherent state where either $\Delta X_1 < 1$ or $\Delta X_2 < 1$. Theoretically $0 \leq \Delta X_1 \leq 1$ or $0 \leq \Delta X_2 \leq 1$ can bee achieved, and X_1or X_2 can be squeezed. The quantum noise is measured with variance, here with $(\Delta X_1)^2$ or $(\Delta X_2)^2$. In squeezed coherent states the noise in one quadrature may be close to zero. This is ideal for communication process.

Reports on cell communication by light were presented[11-14]. Alrecht-buehler[11] cultivated BHK cells on one surface of glass slides, after 2 to 3 days later he inoculated new cells on the other face of the glass slides and cultured continuously in darkness. He found that the growth of the newly inoculated cells was not random, their distribution and orientation were related to the cells on the other surface, but if a piece of metal film was placed between the two faces there is no such phenomenon demonstrating existence of communication by light between the cells[11]. Shen *et al*[12] found that when two population of isolated pig neutrophils were place separately but coupled by light, BPH emissions from one related to the other. In order to study cell communication by light a double chamber system was specially constructed in. Popp's Lab. In this system two measured samples are placed in chamber A and B separately between which there is a shutter. When the shutter opened the two samples can see each other by light, when the shutter closed they can not see each other. BPH emission from each sample is registered by a photomultiplier separately. The distance between the two samples can be changed. Some times during measuring one of the two sample was given an electrical stimulation to study their interactions. Using different material as the test sample we have got similar results [13, 14]. As showed in Fig. 7 when the two cultures of dinoflagellates in the light contact flickering from A (upper) and B (lower) appeared synchronously, closing the shutter their bioluminescence flickerings were not synchronous. This phenomenon can be understood that when the two samples see each other, because of the coherence of lights emitted from them, destructive interference is established that is sensitive to the environment. Any disturbance can be responded by the two samples simultaneously resulting in the increasing photon emission. When the double chamber system was equipped with the coincident device, the properties of the photons from the samples can be measured. In the case of Fig.7 when the shutter was opened (0 to300 sec) the light from *Gonyaulax* measured by CCS was in squeezed state showed in Fig.3. It has been know for a long time that communication between fireflies is a typical model of light communication. By using CCS method distributions of statistics of photons from fireflies *Lampydia* captured in the Beijing hunting park were investigated and the results were given in Fig. 8 where open circles, the solid line and dashed line have same meanings as in Fig.2. The figure shows the distribution of photo count statistics is of Poisson type when fireflies were in the resting condition. Above examples demonstrate that living beings use BPHs in squeezed or coherent states for bio-communication and the "fluorescence" from

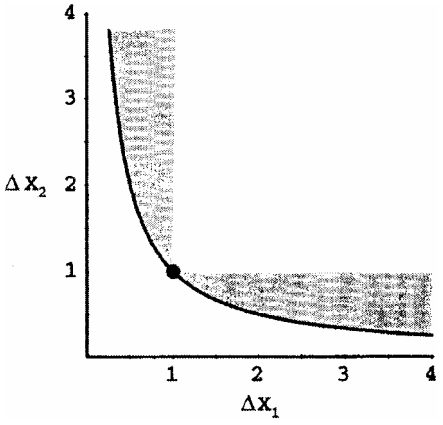

Fig. 6—Heisenberg's uncertainty principle. (Walls and Milbum, 1994, *Quantum Optics*)

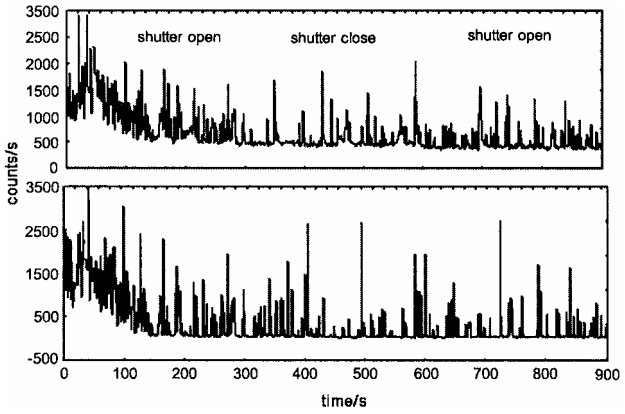

Fig. 7—Synchronous flickering of *Dinoflagellates. Gonyaulax*

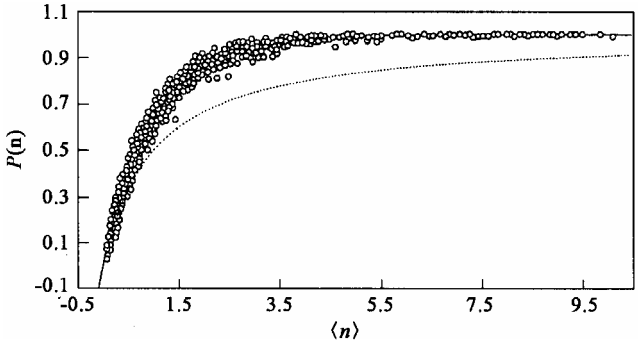

Fig. 8—Distribution of P(n) form Lampyridaes (measured parameters: Δt=0.1s, $\Delta\tau = 10^{-4}$s, $\tau = 10^{-5}$s)

living organism may be regulated by BPH fields within them.

Discussion

The coherent properties of BPH are demonstrated by experimental studies, such kind of photons must play important roles in biological functions. In order to understand the roles of BPHs at first we need to discuss how a coherent BPH field is created and what is the main source for BPHs. Popp considers that DNA may be the main source of the BPH fields. The Q value of DNA in cells can reach to 10^{18} or even higher displaying DNA molecules having strong capacity of storing photons[15]. From structure point of view only DNA molecules can get so high Q value. Based on his theoretical studies Li[16] explains that within DNA molecules, the excited base molecule can form excited dimmer (termed excimer) with the nearest base that is not in excited state. DNA excimer radiation is based on the same principle as laser radiation.

Nucleic acids molecules (RNA and DNA) are constructed with nitrogenous bases (purines and pyrimidines), pentose sugars (ribose or deoxyribose) and phosphate groups, as macro or super-macro molecules. Most DNA molecules in cells are double strands forming a double helix structure in which the two strands are intertwined as two right-handed helices. In "B" form of DNA molecules one turn of the double helix covers 10 base pairs and the spacing of the neighboring base pairs is about 3.4 Å. One molecule of DNA even contains millions of base pairs. Such high ordered helical structure offers bases strong stacking that may provides conditions for stimulated radiation. In living organisms excited bases in DNA molecules do go back not immediately to the ground state thermodynamically but form excimers which are in the meta-stable state, a state far away from thermo-equilibrium. Actually this is the mechanism of DNA storing photons. When providing a certain satisfying energy, in principle within living systems energy supply is enough because metabolic process, the transitions and light radiations take place.

According to the result of the Human genome project, the human haploid cell contains total DNA of about 3×10^9 base pairs, but among them only 1–1.5% encode proteins. Most part of the total DNA neither code for protein nor for RNA. Such kind of DNA contains a lot of repetitive sequences. Up to now the functions of these DNA bases are unknown. From the point view of the properties of BPHs such DNA bases may be necessary for BPH emission that may be a regulating manner of the controlling genes. DNA replication, transcription and proteins synthesis are the key processes and they may be regulated by BPHs. In the Summer School of IIB (International Institute of Biophysics) I have talked about that DNA replication may be mediated by BPH, genetic codon may be working with DNA excimer radiation and BPH may play some roles in DNA transcription. It has been proved that during DNA replication, DNA molecules unwind firstly and then the complimentary new chains must synthesize from 5'→ 3' direction, so that only one strand (the leading strand) replicates continuously in the same direction as the fork going. Okazaki found that the other chain synthesizes in steps, firstly small fragments of nucleotides are synthesized then linked by enzyme. So that both strands can be replicated in the 5'→ 3' direction, but the question is where the Okazaki's fragments start and how it is controlled? Our answer is that BPHs from excimer emission during DNA unwinding may be the controller. In protein synthesis for each amino acid the codon includes 3 nucleotides and except tryptophan, methionine each amino acid has two, three, four even six codons, but the fist two bases are important that may be related with DNA excimers. UAA, UAG, UGA are distinguished as the termination codons, but AUG for initiation codon. If asked why some works for termination and some for initiation? How the whole protein synthesis process is regulated?, we may have to consider excimer formation and their radiation. Different bases have different electron energy distributions that correspond to light radiation differently. Even the very small deference appearing in the radiation of excimers corresponding to different codons but can be recognized by the right DNA bases as well as by the

special amino acids. Recently a new picture about RNA functions and DNA transcription was drawn out. RNA molecules are not just to transfer genetic message but to actively regulate cellular processes. During genome DNA transcription, many segments of genes convert into multiple RNA ribbons which can be generated from both strands. Gene DNA transcription may be controlled by regulatory regions even in other chromosomes [*Nature*, 441 (2006) 399]. During gene transcription the long distance regulative functions may be performed by BPH.

Identities of proteins are 3-D spatial structures and having a certain conformation for their activities and functions. Proteins may work as non-linear crystals to squeeze light and this is why living organisms can emit squeezed light. BPHs caused by conformation changes of proteins may play a role for protein activities and functions. Concerning with cell signaling process, there are many pathways for extra cellular signals getting into cells and transmitting within cells, but mostly they are commonly in steps. For instance, in the cAMP pathway in general, the signal transmits as follows: when outside signal combines with the receptor on cell surface (step 1) that stimulates the receptor. The activated receptor stimulates G protein (step 2) which then stimulates adenylate cyclase (step 3). The activated cyclase enhances the concentration of cAMP (step 4) which stimulates protein kinase A (step 5). The activated kinase A gets into cell nuclei, further passing several more steps reaches regulating the gene express. Each step combined some change that may emit BPHs which can be recognized by the next, or by some even by all events (may be by frequency). In other case it seems that the BPHs signals may transmit within channels and the microtubules may play the role of optical guides during cell division. Neurofilaments are characteristic of neurons and most numerous neurofilaments are in axons where they parallel to the axis of the axons and distribute together with microtubules. Presumably one of the neurofilament's functions is to act as transmission channels for photon signals.

The activities of life need energy which is derived from ATP. In a human body, every day the cells produce about several Kg of ATP and more than 95% of the ATP are synthesized in mitochondria. The foods are digested in stomach and catabolized into small molecules in cell cytoplasm, then the small molecules enter in mitochondria where some of them (pyruvate and succinic acids) dehydrogenate and release H^+ and e^-. The electrons are transported by a series of carriers called electron transport chain or respiratory chain to O_2 , finely, $1/2\ O_2 + 2\ H^+ + e^- \rightarrow H_2O$ + energy which is used to synthesize ATP.

Up to now there are several hypothesis concerning the mechanism of electron transport in oxidative phosphorylation, however a few questions still remain unanswered. It has been reported that in the mitochondrial respiratory membrane Complex II, the distances between electron carriers is about 8.9Å (in the minimum) to 13.3 Å (at the maximum) with their edge-to-edge[17]. The distance is too big for movement and collision of the electron particles, although there is the gradient of redox potentials between these carries. Electron transport actually is energy transfer, that should take place as wave transmission which may performed by coherent fields.

Photosynthesis, carried out by green plants, eukariyotic algae, and photosynthetic bacteria, is a process producing organic molecules and releasing oxygen by using sun light, water and carbon dioxide. This is a complicated process involving following three steps: (i) primary reaction, (ii) electron transport and photo-phosphorylation, (iii) CO_2 assimilation. The first two steps as light reaction are carried out in thylakoid membranes of chloroplasts, the third as dark reaction is carried out in stroma of chloroplasts. The basic functional unit of photosynthesis is photosystems PS I and PS II, each of which has reaction centre and light harvesting centre (LHC). The pigments attending in photosynthesis in green plants are comprised by chlorophylls (Chl a and Chl b), caroteniods (β-carotene and xanthophyll), but only some of them (antenna) can absorb solar energy and deliver the absorbed energy through resonance (commonly accepted manner as of now) to other pigments, finely to special Chl a P700 (in PS I) and Chl a P 680 (in PS II) where electrons are pushed into at the elevated energy levels. In the second step the electrons released from water in relating with Chl a P 680 state changing are transported in a similar manner as in mitochondria to synthesize ATP. The electron transport in photosynthesis is more complicate than in mitochondria but should be in principle similar. To answer the question of what is the mechanism for the excited light energy transferring BPHs have to be considered. Many experimental studies already showed the hyperbolic decay of re-emission from leaves illuminated by light and around the decay

curve with oscillations displaying the interactions (coherent relation) among different elements (pigments and/or proteins) and they are in a coherent field. Engel *et al*[18] using 2-d Fourier transfer electric spectroscopy investigated bacterial-chlorophyll complex (from LHC to the reaction center), they observed the quantum beating (oscillation) signals at 77K that shows quantum coherence play an important role in energy transfer process within this system.

The BPH fields are in coherent and squeezed states suggesting that over a long period of life evolution livings learned how to used quantum mechanism to regulate themselves. This is the most important edification from investigating properties of BPHs. The BPH field just is a part but an important part of the electromagnetic fields in living organisms. Frohlich elucidated in 1968 that living systems can be expected to have intrinsic microwave[19]. So far experimental reports confirmed that during cell division the output frequency can reach about to 80 MHz in yeast cells, 1 to 30 kHz in birds and mammalian cells[20]. Besides, there are electric fields, magnetic fields, attraction and gravity fields within living organisms. Each of them plays their function in certain respect. In living systems ions play important roles as well. To learn BPHs it is necessary to understand the life, to learn their functions and interactions with other internal and external fields including with the sun light. The essential truth is that the life on the earth is developed and evolved permanently under the sun and the other fields.

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References

1 Popp F A, Some essential questions of biophoton research and probable answers, in *Recent advances* in *biophoton research and its applications*, edited by F A Popp, K H Li & Q Gu (World Scientific Publishing Co., Singapore-London) 1992, 1.

2 Popp F A, Biophtons-background, experimental results, theoretical approach and applications, in *Biophotonics*, edited by F A Popp & L Beloussov (Kluwer Academic Publishers, Dordrecht-Boston-London) 2003, 387

3 Galle M, Neurohr R, Altmann G & Nagl W, Biophoton emission from *Daphnia*: A possible factor in the self-regulation of swarming, *Experientia*, 47 (1991) 457.

4 Schamhart D H J & van Wijk R, Photon emission and the degree of differentiation, in *Photon emission from biological systems*, edited by B Jezowska -Trzebioatowska, B Kochel & J Slawinski (World Scientific Publishing Co., Singapore-London) 1987, 137.

5 Scholz W, Staszkiewicz U, Popp F A & Nagl W, Light stimulated ultra-weak photon reemission of human amnion cells and wish cells, *Cell Biophysics*, 13 (1988) 55.

6 Popp F A & Li K H, Hyperbolic relaxation as a sufficient condition of a fully coherent ergodic field. *Int. J. Theor. Phys*, 32 (1993) 1573.

7 Popp F A & Yan Y, Delayed luminescence of biological system in terms of coherent states, *Phys. Lett. A,* 293 (2002) 93.

8 Popp F A & Shen X, The photocount statistic study on the photon emission from biological system using a new coincidence counting system, in *Biophotons*, edited by J J Chang, J Fisch, F A Popp (Kluwer Academic Publishers, Dordrecht-Boston-London) 1998, 87.

9 Popp F A, Chang J J, Herzog A, Yan Z & Yan Y, Evidence of non-classical (squeezed) light in biological systems, *Phys. Lett, A*, 293 (2002) 98.

10 Chang J J, Biological effects of electromagnetic fields on living cells, in *Biophotonics*, edited by F A Popp & L Beloussov (Kluwer Academic Publishers, Dordrecht-Boston-London) 2003 , 231.

11 Albrecht-buehler G, Rudimentary from of cellular " vision", *Proc. Natl. Acad. Sci. USA*, 89(1992) 8288.

12 Shen X, Mei W P & Xu X, Activation of neutrophils by a chemically separated but optically coupled neutrophil population undergoing respiratory burst, *Experientia*, 50 (1994) 963

13 Popp F A, Chang J J, Gu Q & Ho M W, Non-substantial biocommunication in terms of Dicke's theory, in: *Bioelectrodynamics and biocommunication*, edited by M W Ho, F A Popp & U Warnke (World Scientific Publishing Co., Singapore-London) 1994, 293.

14 Popp F A & Chang J J, Mechanism of interaction between electromagnetic fields and living organisms. *Science in China (C)*, 43 (2000) 507.

15 Popp F A, Coherent photon storage of biological systems, in *Electromagnetic Bio-Information,* edited by F A Popp, U Warnke & KÖnig H L (Munchen-Wien-Baltimore, Urban & Schwarzenberg) 1989, 144.

16 Li K H, Coherent radiation from DNA molecules, in *Recent advances in biophoton research and its applications*, edited by F A Popp, K H Li & Q Gu (World Scientific Publishing Co., Singapore-London) 1992, 157.

17 Hagerhall C, Succinate:qinone oxidoreductases. variation on a conserved theme, *Biochim. Biophys. Acta* (1997) 107.

18 Engel G S, Calhoun T R, Read E L, Ahn T-K, Mancal T, ChengY-C, Blankenship R E & Fleming G R, Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems, *Nature*, 446 (2007)782.

19 Froehlich H, Long-range coherence and energy storage in biological systems, *Int. J. Quant. Chem*., 2 (1968) 641.

20 Hyland G J, Bio-electromagnetism, in *Biophotonics*, edited by F A Popp and L Beloussov (Kluwer Academic Publishers, Dordrecht-Boston-London) 2003, 117.