About the Coherence of Biophotons

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Abstract

Biophoton emission is a general phenomenon of living systems. It concerns low luminescence from a few up to some hundred photons-per-second per square-centimeter surface area. At least within the spectral region from 200 to 800nm. The experimental results indicate that biophotons originate from a coherent (or/and squeezed) photon field within the living organism, its function being intra- and inter-cellular regulation and communication.

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1 - Introduction

Biophotons are photons emitted spontaneously by all living systems **[1-3]**. In particular, this phenomenon is not confined to "thermal" radiation in the infrared range. It is well known at present that biophotons are emitted also in the range from visible up to UV. Actually, the intensity of "biophotons" can be registered from a few photons-per-second per square-centimeter surface area on up to some hundred photons from every living system under investigation.

The spectral distribution never does display small peaks around definite frequencies. Rather, the quite flat distribution within the range of at least 300-to-800 nm has to be assigned to a thermodynamical system "far away" from equilibrium, since the probability **f(*υ*)** of occupying the phase space is on average almost constant and exceeds the Boltzmann distribution in this spectral range by at least a factor of 10^{10} (in the red) up to 10^{40} (in the UV-range). [$f(\upsilon)=n\upsilon\ (c^2/2\upsilon^2)(F^{-1})$ where $n\upsilon$ is the

measured spectral photon intensity per unit of solid angle. F is the area of the subject. For a system in thermal equilibrium, ***f(υ)=exp(-hυ/kT)*** where ***hυ*** is the energy of the photon and ***kT*** the mean thermal energy.]

Fig. 1 displays a typical frequency distribution of a living system where the spectral intensity of biophotons (at the outside of the living system) has been averaged over several measurements and then expressed in terms of the excitation temperatures (upper figures and lower left figure) or the occupation probability **f(*υ*)** (lower right figure). The term "bio" in biophotons has been introduced **[4]** in the same way as it has been done in the term "bio-luminescence", pointing to the biological source of the emission. And the term "photons" in the word "biophotons" has been chosen to express the fact that the phenomenon is characterized by measuring single photons, indicating that this phenomenon has to be considered as a subject of Quantum optics rather than of Classical physics.

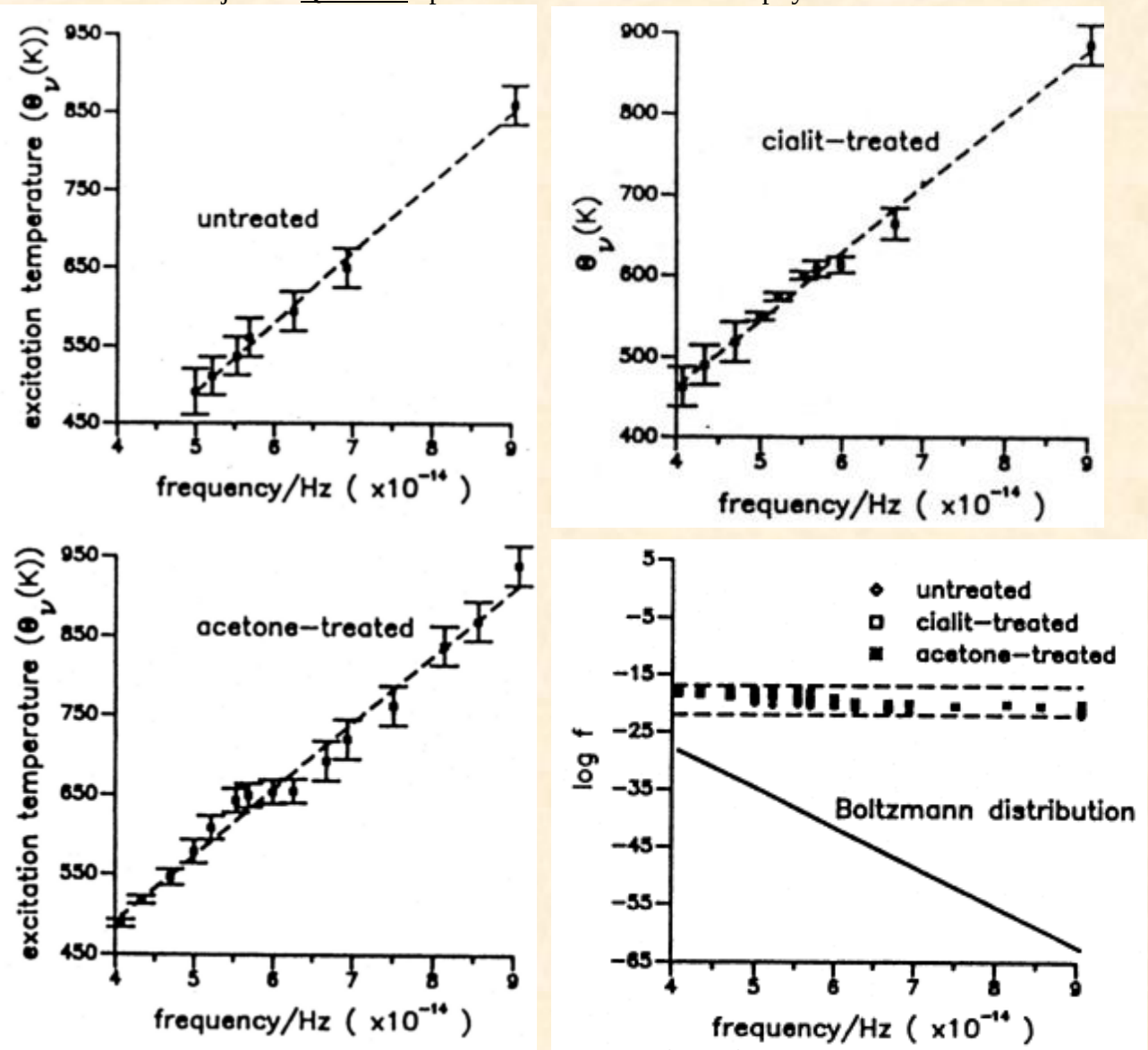

Figure 1: Excitation temperature $\theta(\upsilon) = h\,\upsilon / k\, ln(2\upsilon^2 F / c^2\, n\, \upsilon)$ of cucumber seedlings under different treatments and the ***ln(f(υ))*** -value compared to the Boltzman ***ln(f(υ)).***

Given this background, we understand that 2 completely opposite interpretations of this phenomenon come up -- the **biochemical theory** (BCT) and the **coherence theory** (CT). It is amazing that both the BCT and the opposite "biophysical theory" CT take the rather low intensity as an essential point in their arguments.

According to the BCT [5, 6], biophoton emission is some kind of "waste" of the metabolic events taking place permanently within the cells. The BCT indicates some imperfections in chemical reactions which (by returning to thermal equilibrium) emit overshoot energy of chemically induced optical transitions, mainly linked to radical reactivity of oxidation processes.

On the other hand, the CT points to the low intensity as an indication of non-Classical light which may display even sub-Poissonian photocount statistics and may thus provide an optimized optical communication channel in biological systems within living matter of "optimized" high optical density [2].

It is impossible to decide after measurements of the spectral intensities whether the BCT or the CT reflect the truth since ordinary physical properties of biophotons may not distinguish one or the other theoretical approach. A similar situation would occur if somebody constructed a squeezed light source of a many-mode photon field. No one could answer the question of coherence as long as only the spectral distribution of the light emission is known.

The unsolved problem of biophoton emission forces us to look for experimental evidence of either the coherent or the chaotic nature of the biophoton field. If is possible to show evidence of an extraordinary high degree of coherence of biophotons, then the conclusion follows that this universal phenomenon of biological systems is responsible for the information transfer within-and-between cells, answering then the crucial question of intra- and extra-cellular biocommunication including the regulation of the metabolic activities of cells as well as of growth and differentiation and even of Evolutionary development.

In order to reveal the importance of the experimental research and the significance of the results which have been obtained up to now, let us briefly characterize some essential activities of a cell concerning the necessity of optical transitions and then confine ourselves to the main experimental results on the physical problem of coherence. Then we can go back again to some basic biological phenomena where the non-linear coupling of biophotons and living matter becomes evident. We will then show that an understanding in terms of the coherence of biophotons is consistent with all the observations, while the BCT does not allow us to explain all the physical and biological effects under study. We are even convinced that experimental evidence of the coherence of biophotons can be drawn from the experimental results.

2 - Preliminary Remarks on the Biological Situation

An ordinary cell has a diameter of about 10^{-3} cm. Inside this cell, there is in general a rather high metabolic activity of about 10^5 reactions per second. For every reaction, the suitable activation energy (in the range from microwaves to ultraviolet) is necessary to establish the formation of the transition state complex [7] which decays finally into stable chemical product(s). As Cilento has shown [8], some (if not all) biochemical reactions take place in the way that a photon is borrowed from the surrounding electromagnetic bath. Then it excites the transition state complex and finally returns to the equilibrium states of the surroundings, becoming thus available for the next reaction.

Whatever the detailed mechanism may be, a single photon may suffice to trigger about 10^9 reactions per second since the average reaction time is of the order of 10^{-9}s and provided -- in addition -- that it is directed in a way that it delivers the right activation energy as well as the right momentum at the right time to the right place. This means that a surprisingly low photon intensity may suffice to trigger all the chemical reactions in a cell in the case of a rather refined dirigent who is permanently controlling the

whole field. That this dirigent is not a thermal field in a living system (where the dirigent would be a perfect chaot) can be readily seen in **Fig. 1**.

One has to note that despite the low intensities, at any instant at least 10^{10}-to-10^{40} more photons are available than under thermal equilibrium conditions. This explains for instance the well-known fact [9] that in a cell some of the reactions are much faster than under thermal equilibrium conditions. Note that a temperature increase of 10 degrees doubles already the photon density of a thermal field under physiological conditions, resulting consequently in a doubling of reaction rate. The spectral intensities of the biophoton emission have to be assigned to the excitation temperatures of **Fig. 1** which are much higher than physiological temperatures. This shows clearly that with respect to biophotons,

- the biological system is far away from thermal equilibrium, and
- biophotons may well provide the necessary activation energy for triggering all biochemical reactions in a cell at the right time at the right place.

Concerning the coherence of the biophoton field which could explain as well the presence of the "dirigent" and its high efficiency, it is worthwhile to note that a photon in a cell displays always a significant partial degree of coherence in the ordinary sense. Take as an example an allowed optical transition of a lifetime (coherence time) of say 10^{-9}s. In this time, the emitted electromagnetic wave packet travels over a distance or 10 cm which is 10^4 times longer than the diameter of a cell.

Therefore, it is rather unrealistic to believe that the phase information gets lost over the space of a cell. Or even to speak generally of single photons in a cell and to assign to them to single small molecules from which they might originate. In reality, we are faced with a biological situation where a probability field of electromagnetic wave amplitudes may localize and delocalize in a spatio-temporal manner in a highly flexible but probably **even** rather deterministic interaction with the surrounding matter. Instead of single photons, we have to take account of rather refined **interference patterns** of electromagnetic fields where the spatio-temporal resolution may range over many orders from nanometers to meters and more, and from nanoseconds to seconds and even longer time intervals.

In view of the permanent electromagnetic interaction of radiation and matter in the optically dense medium of a cell, it cannot be ruled out that an electromagnetic field of a surprisingly high degree of coherence may accumulated to such an extent that each molecule in the system is connected (or has the capacity to get connected) to every other one. The conditions under which this can happen have to be carefully investigated as soon as the evidence of coherent electromagnetic fields in biological system appears.

3 - Evidence of the Coherence of Biophotons

It is well known [10] that a necessary condition of coherence of an ergodic stationary electromagnetic field is the Poissonian distribution of its photocount statistics (PCS). This fact is based directly on the definition of coherent states as eigenstates of the annihilation operator.

Actually, the representation of a coherent field in terms of number states leads to the probability amplitudes $\mathbf{\langle n|\alpha\rangle=\exp(1/2|\alpha|^2)\ \alpha^n/\sqrt{n!}}$ where $\mathbf{|n\rangle}$, $\mathbf{|\alpha\rangle}$ are the number states and coherent states, respectively.

Consequently, if one prepares a biological system in a stationary state and measures the PCS, one is able to examine whether this necessary condition of coherence of biophotons is fulfilled or not. We

started these measurements in 1981 [11] and continued with more and more refined methods up to now. After direct methods where we compared the measured statistical distribution with the best fit of a Poissonian distribution, we changed to measurements of the normalized factorial moments which have the advantage of being independent of special properties of the photomultiplier [2]. As long as the normalized factorial moments of all orders keep the value 1, one can be sure that the PCS is Poissonian.

It turned out that in a quasistationary state, all biological systems under study approach rather accurately a Poissonian PCS (**Fig.2**) [12].

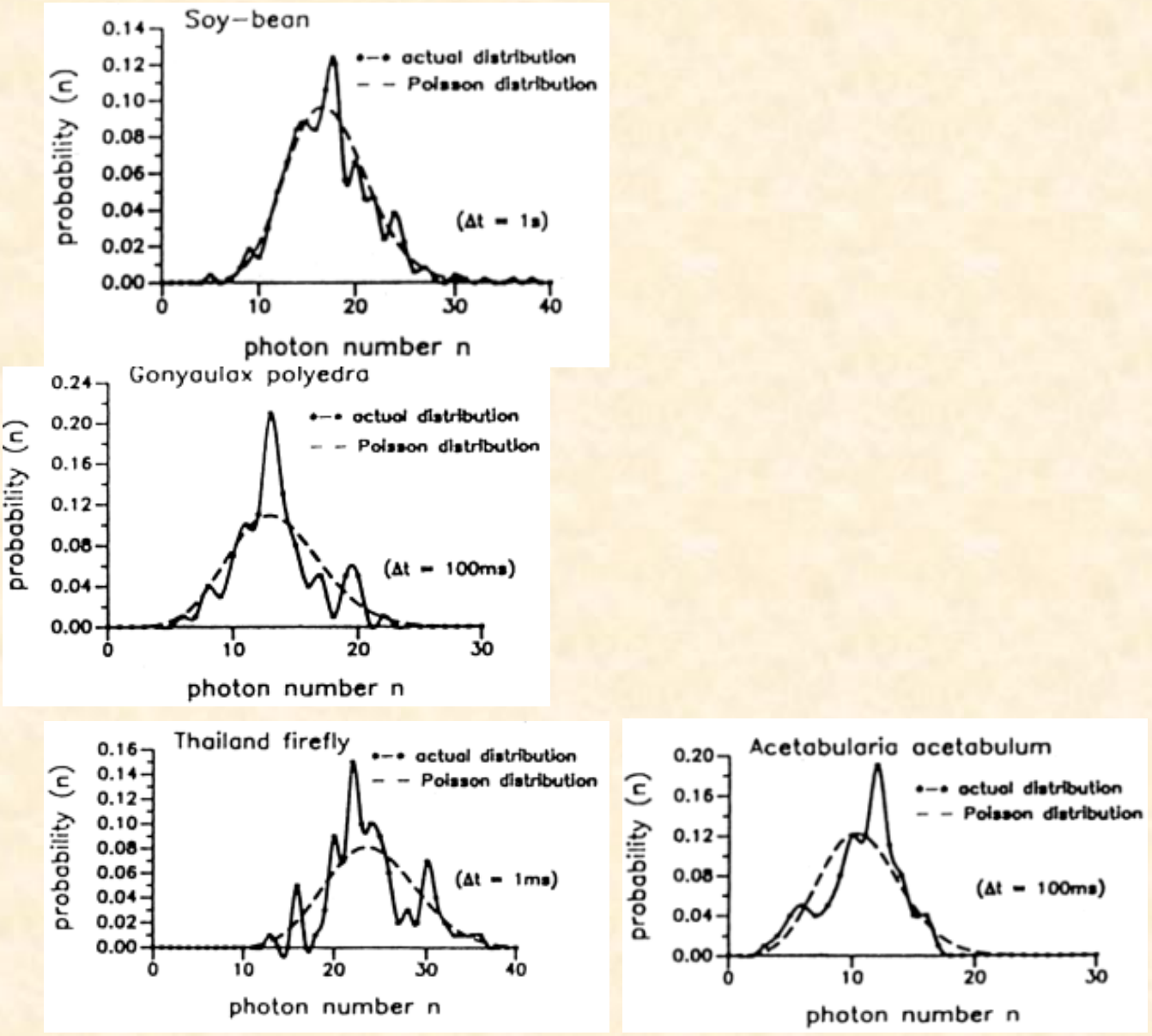

Figure 2: Agreement of the Photocount Statistics of different biological systems with a Poissonian distribution.

It is important to know whether the Poissonian distribution is only some kind of an average over the measurement time interval or whether it is valid at any instant. In the first case, it could be an indication of a chaotic field which in a small time interval (compared to its coherence time) follows a geometrical distribution. But with increasing measurement time, it approaches more-and-more a Poissonian distribution.

Consequently, in the case of a sufficiently long measurement time interval that is large compared with the coherence time of a chaotic field, one would measure a Poissonian distribution as well for a chaotic field as for a fully coherent field. Consequently, as soon as there is no knowledge about the coherence time of a chaotic field, there may be no way of distinguishing with certainty a fully coherent and a chaotic field.

This was the reason why we changed the measurement time interval to rather low values and always measured the PCS **[13]**. We hoped to see then the possible changes in the Poissonian distribution. As far as we have results, there is no indication that with a decreasing measurement time interval down to 10^{-5}s, there is a less accurate agreement to a Poissonian distribution. In fact, we found just the opposite where with decreasing measurement time interval, the normalized factorial values approached better-and-better values around 1 (and even lower). Whereas with increasing measurement time intervals up to 10s and more, the PCS of some amoebae had the tendency to follow a geometrical distribution **[2]**. However, because of the rather difficult procedure of keeping a biological system in a stationary state and the uncertainties of measuring at the outside but not within the living system, do not allow us at present to draw final conclusions from these observations.

It is very important to find out whether the Poissonian distribution of PCS governs the system at any instant (even in a nonstationary state). In the case of a Poissonian distribution at any instant during relaxation after the system has been excited, it has been shown that the relaxation dynamics is ergodic and follows a (**1/t)** law where **t** is the time after excitation **[14, 15]**. The agreement of relaxation dynamics of biophoton emission after excitation to hyperbolic **(1/t)** law and the disagreement to exponential decay including the validity of the Poissonian distribution at any instant are therefore sufficient conditions for a fully coherent ergodic field **[14, 15]**.

It is now accepted that all living systems display hyperbolic relaxations dynamics rather than an exponential one **[12]**. Even the theoretically possible multi-exponential decay can be truthfully excluded by describing the relaxation function of delayed luminescence. Consequently, there is already proof of the coherence of biophotonic emission.

In order to demonstrate experimentally that the hyperbolic decay is a consequence of instantaneous Poissonian distribution during relaxation, we built a double measurement chamber with 2 multipliers and registered the coincidences of counts during the "delayed luminescence" of biological systems. The double chamber is built up in such a way that Channel '1' measures the photon counts of a system under investigation in chamber '1', while Channel '2' registers the counts of an other system in chamber '2. By a Channel '3', the coincidence rate between Channel '1' and Channel '2' are registered. A photon in Channel '2' is registered in Channel '3' as a coincident one as soon as at least one other photon has been counted in Channel '1' in a preset time interval **dt** before the photon counting happens in Channel '2' (**Fig.3**).

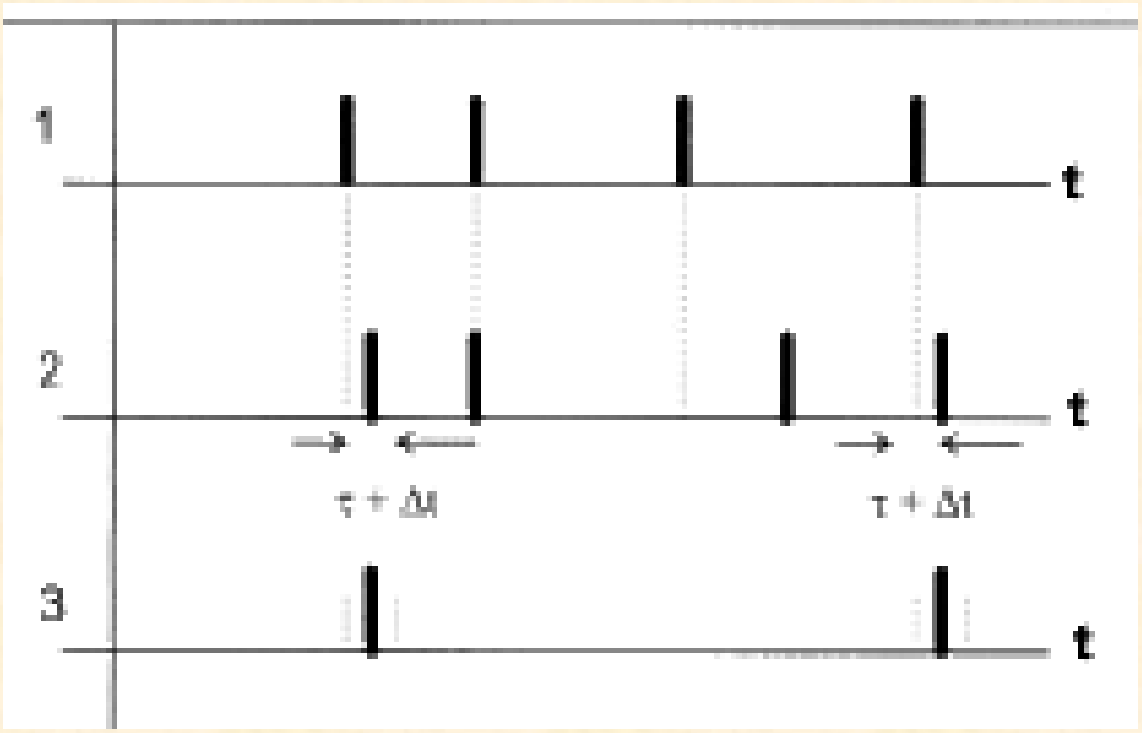

Figure 3 Coincidence counting of biophotons, where at least one photon in Channel '1' has to be registered in a time interval $t< \tau < t+\Delta t$ before a registered photon in Channel '2'.

For $\tau=0$, the number of random coincidences Zj in the j-th time interval is then $Zj = n_{2j} . pl(dt, n_{ji}>0)$, where n2j is the number of counts in Channel '2' within the j-th time interval dt, and p1 $(dt, n_{ij}>0)$ is the probability of counting at least one photon in Channel '1' in a time interval dt. Since $pl(dt, n_{jj} >0) = 1-pl(dt, n_{jj} =0)$ where $pl(dt, n_{jj} =0)$ is the probability of measuring no photon in dt in channel 1, we then have $Zj = n_{2j} -(1-p1(dt, 0))$.

Consequently, by observing the delayed luminescence of a biological system in Channel '1' and another arbitrary system in Channel '2', we register Zj and n_{2j} and are able to compare the measured value $p1(dt, 0) = (1-^{Zj}/ n_{2j})$ with the theoretical one of a Poissonian distribution which is simply $p1(dt, 0) = \exp (-n_{1j}.dt)$. **Fig. 4a** displays the result of such a measurement. It is obvious that the Poissonian distribution of PCS of a biological system is valid at any instant of the relaxation giving rise to the hyperbolic relaxation (**Fig.4b**) and showing evidence that the biophotons originate from a fully coherent field. On the other hand, a geometrical distribution according to $p1 (dt, 0) = 1/(1+ n_{1j}.dt)$ can be truthfully excluded.

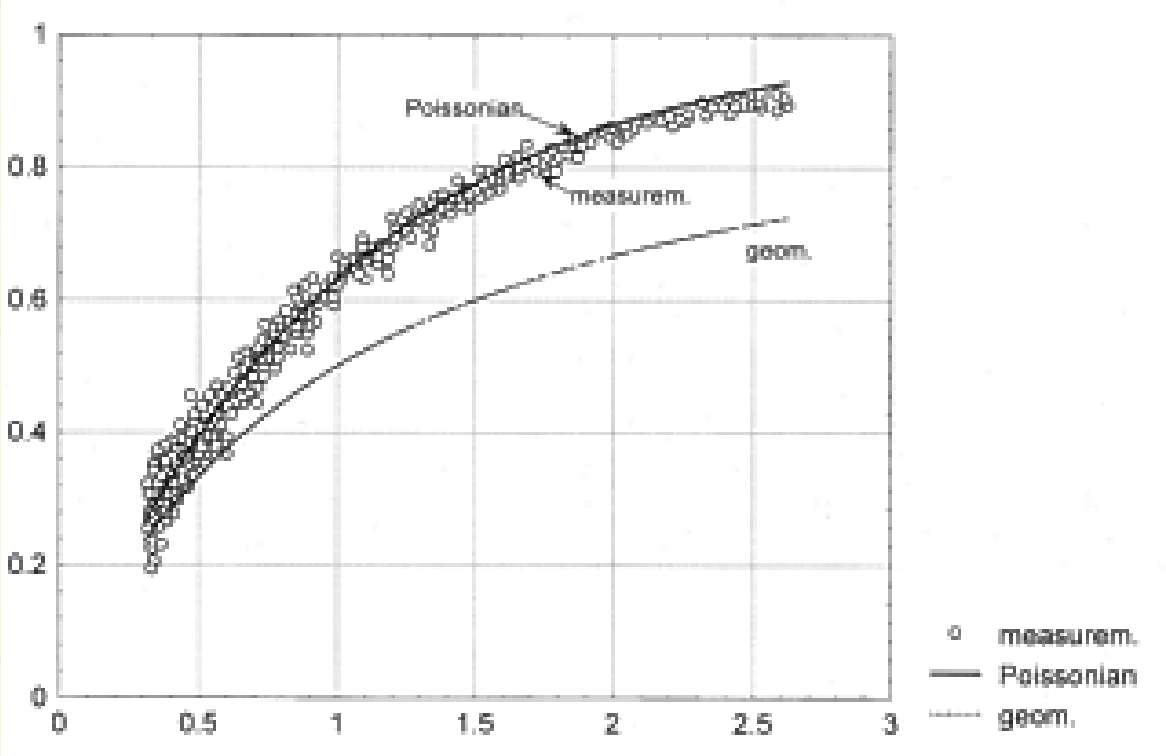

Figure 4a Agreement of the Poissonian distribution with the PCS of biophoton emission of a leaf. The value Zj/n_{2j} is displayed in dependence on $1_{2j}.dt$.

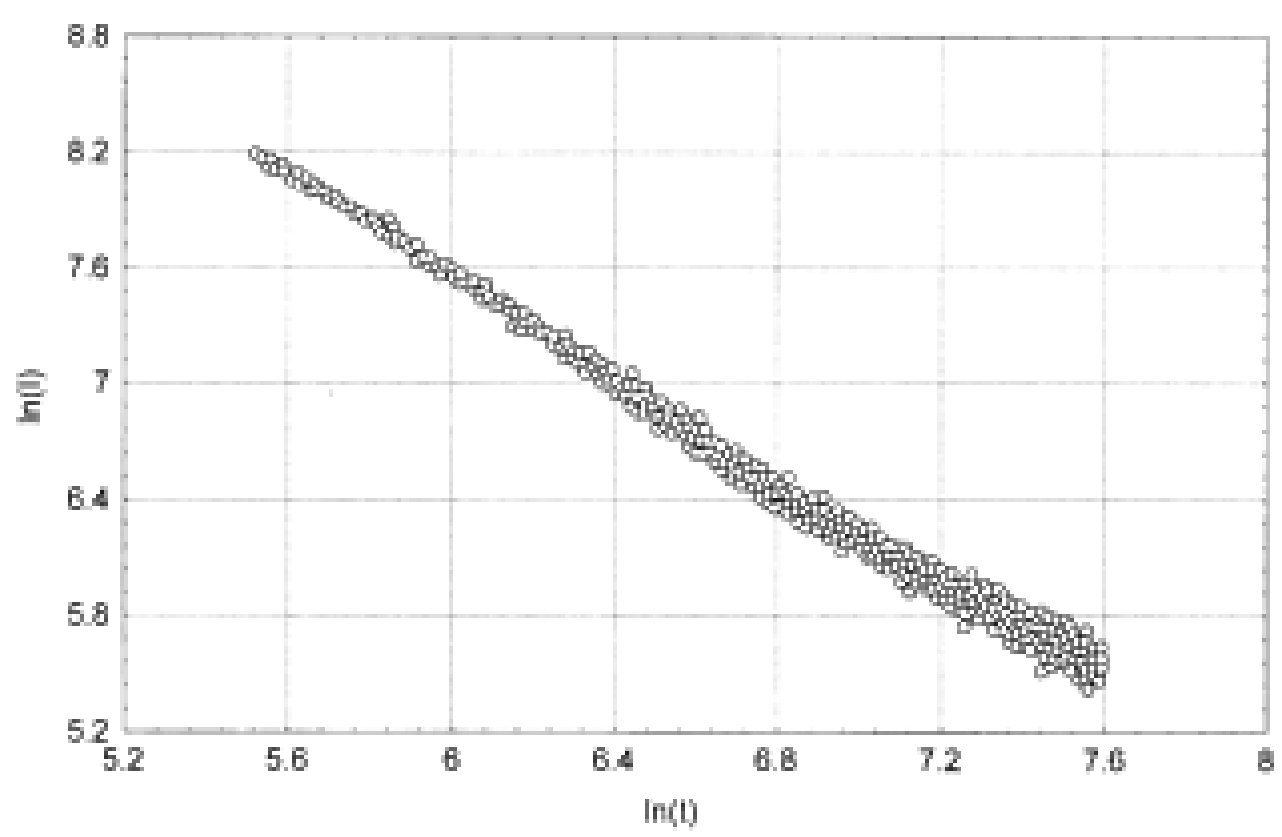

Figure 4b Relaxation of the leaf of Figure 4a, where the logarithm of the intensity is displayed versus the logarithm of the time.

4 - Biological Implications

From the physical point-of-view, one is in the situation to consider whether one can add more results in order to demonstrate more accurately the validity of the coherence theory and to reject the BCT. A list of results and arguments which display some inconsistencies of BCT and the complete agreement of CT with the known phenomena has been published elsewhere **[2, 3]** and is not repeated here.

There have also been some ideas and some physical models that can explain the molecular mechanism of coherent biophoton emission **[2, 3]**. The most likely candidate for biophoton emission is the **chromatine** of the cells in a non-equilibrium state where probably the exciplexes of the DNA are essentially involved. Actually, red blood cells which have no active chromatine are the only cells which do not emit biophotons. In addition, there are clear correlations between biophoton emission and the intercalation of inert substances like ethidium bromide into the DNA **[16, 17]**.

The most basic understanding of the coherence of biophotons can be derivated from Dicke's theory of **sub-radiance** and **super-radiance** **[18]** which is valid for optically dense media. Actually, the interaction of electromagnetic waves with large wavelengths compared to the antenna systems of a cell leads to non-exponential relaxation functions and -- in particular for sub-radiance -- to delayed luminescence. The phase-information within and between cells can then hold a rather important biological control parameter which may regulate the growth and differentiation of cells.

If this is the case, one expects non-linear dependence of biophoton emission from biological functions. Actually, we found deviations from Beer-Lambert's law for light traveling through cellular layers **[19]**. A convincing result is the non-linear change of biophoton emission from Daphnia magna (**Fig. 5a**) **[20]** and the nonlinear change of delayed luminescence from normal and cancer cells (**Fig. 5b**) **[21, 22]**. At the same time, the agreement with a hyperbolic relaxation dynamic increases with increasing cell density of normal cells and it decreases for malignant cells.

All the results can not be interpreted in terms of the BCT but can be well understood by using the CT. Of course, the capacity for destructive interference between the cells -- and consequently the preference for constructive interference within the cells -- provides a powerful communication system. As soon as mutual constructive interference of the specific wave patterns of the biophotons within the cells is optimized (and at the same time destructive interference outside is as perfect as possible), a rather unstable equilibrium is obtained where every perturbation works as a common signal of the highest possible signal/noise ratio **[2]**. While normal tissue follows this optimization principle, tumor tissue has lost this capacity by a critical loss of coherence. As a consequence, tumor cells are not more able to display destructive interference and not able to communicate.

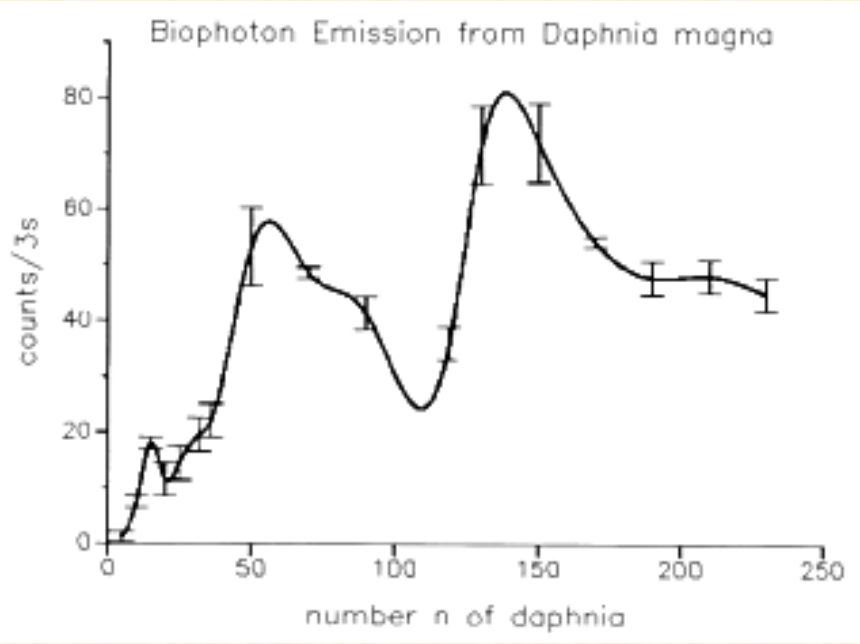

Figure 5a Biophoton Emission of Daphnia magna with increasing number of animals.

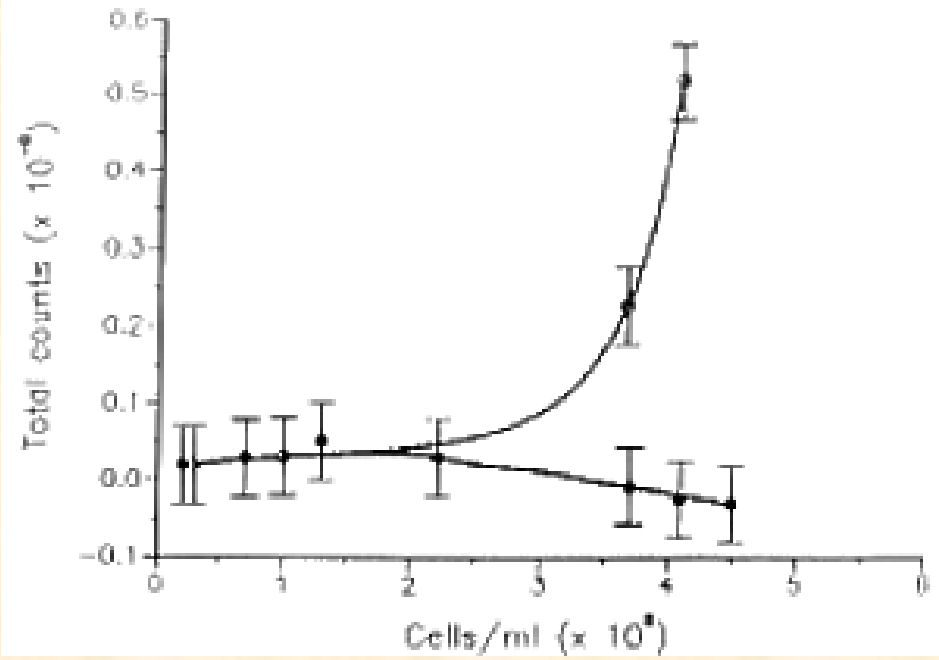

Figure 5b Delayed luminescence of cancer cells (upper curve) and normal cells (lower curve) in dependence on the cell density.

5 - Conclusions

There is evidence that biophotons originate from an almost fully coherent field. Deviations from coherence can be assigned to biological aberrations.

However, even from a physical point-of-view, a variety of problems awaits better solutions. A great deal of work has to be done in order to reveal the molecular basis of biophoton emission. Not only have possible sources such as exciplex states of DNA to be investigated, but also the stabilization criteria of coherent states under the different biological and physiological conditions.

A lot of future work has to be devoted to the question of "squeezed light" which may be involved in biophoton emission [2, 12].

Since destructive interference in the intercellular space and constructive interference in the intracellular space is likely to be the most important mechanism of biological organization, one has to give an answer to the question of how a cell (working on phase information) is able to react to external light in such a way that it performs constructive interference inside at the cost of destructive interference on the outside. We like to note here that this mechanism may be the reason for photon-suction which is observed for instance in sunflowers which are able to turn the flowers perpendicular to direction of the sun-ray momentum.

We propose a mechanism which is based on the identity of **D(0) - ½ (D(A)+D(-A))** for coherent states. Which means that the displacement operator **D(0)** of the vacuum state is not just the geometric, but also the arithmetic mean of displacements operators of opposite wave amplitudes **A** and **-A**. This is at the same time a sufficient condition for coherence as well as the reason why excited coherent states relax according to a hyperbolic function [15].

A further field concerns the technical improvement of the instruments. The signal/noise-ratio has to be considerably improved while maintaining the high sensitivity. Future biophoton analysis will be based on measurements of the spectral intensities of biophoton emission as well as of delayed luminescence after definite excitation by electromagnetic radiation (including light) and ultrasound. Also, the temperature response of biophoton emission contains valuable information of the living matter under study. The analysis will be extended more-and-more to the normalized factorial moments and to the relaxation dynamics under different conditions.

"Biophotonics" covers already a wide field of applications (e.g.,. basic biological research [23], food quality control, cancer research [4, 26], pharmacology [27], health prophylaxis including whole-body counting of biophotons [28]. The techniques in all these fields can be considerably improved in order to develop biophotonics into one of the most powerful non-invasive tools of investigating life with light.

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