ELSEVIER Applied Mathematics and Computation 93 (1998) 277–288

APPLIED MATHEMATICS AND COMPUTATION

Biophoton emission in the evolution of a squeezed state of frequency stable damped oscillator

R.P. Bajpai *, S. Kumar, V.A. Sivadasan

Institute of Self Organising Systems and Biophysics, North-Eastern Hill University, Shillong, Meghalaya 793022, India

Abstract

A model to explain the relaxation behaviour of a biophoton signal is developed. The model assumes that every biological system is endowed with a non-classical electromagnetic field in a squeezed state. The quantum evolution of the state determines the shape of the signal. It is illustrated by considering the evolution of a single mode field described by a frequency stable damped oscillator. The model predicts a relaxation behaviour in the form $n(t) = B_0 + B_2(1 + \lambda_0 t)^{-2}$. The coefficients B_0 and B_2 depend upon the initial state of the field and are situation specific. The constant λ_0 is determined by the damping of the field and is system specific. The model explains in a natural way two characteristic features of biophoton signals, namely non-exponential decay of light induced emission and constant flux of spontaneous emission. The model is applied to the light induced photon emission in flowers of *Tagetes Patula*. The value of the damping coefficient λ_0 in this system is found to be $(0.040 \pm 0.011)\mathrm{s}^{-1}$.

Keywords: Biophoton; Squeezed state; Non-exponential relaxation; Frequency stability; Light induced emission

1. Introduction

Living systems continuously emit photons of ultra weak intensity in the visible range. These are called biophotons [1]. The biophoton signal depends upon

* Corresponding author.

0096-3003/98/$19.00 © 1998 Published by Elsevier Science Inc. All rights reserved.
PII: S0096-3003(97)10117-5

many environmental and physiological factors. The shape of the signal and its dependence upon these factors rule out the origin of biophotons from chemiluminescence, bioluminescence, fluorescence and super fluorescence [1–3]. The origin and source of biophotons [4] are yet to be established. The phenomenon of biophoton emission is divided in two classes – spontaneous and light induced [2,5]. The photon flux in spontaneous emission is nearly unchanging for hours. The flux is ultra weak and its measurement requires sensitive detectors approaching the quantum mechanical limit. The photon flux in light induced emission is more intense but lasts only for a short while [5]. The signal decays to the level of spontaneous emission in a few minutes. The decay has a non-exponential relaxation behaviour [6]. The strengths of the decaying signal vary from system to system. The light induced emission is more intense in photosynthetic systems. The peak intensity of the signal is 2–3 orders of magnitude higher than the intensity of the signal in a spontaneous emission [7]. The experimental data have been parametrized using multi-exponentials [8,9], hyperbolic [10] and other types of functions [11]. Constant flux in spontaneous emission and non-exponential relaxation behaviour in light induced emission are two unexplained characteristics. It is difficult to incorporate them in existing models. One requires a new approach to understand biophoton emission. Such an approach is presented in this paper in which both features emerge in a natural and unified manner.

We envisage that every living system is endowed with an endogenous electromagnetic field. The field is in a pure quantum state. The quantum state is a squeezed state of the photon with time dependent parameters. The state evolves in a definite manner. The evolution determines the shape of the signal. It is assumed that the state of the biophoton field and its dynamics can be represented by the motion of a damped oscillator with time dependent damping and mass terms. These terms are such that the mode frequency is not altered. Many different damping terms are permissible. They generate signals of similar shapes in our approach. We shall illustrate our approach by obtaining the shape of the signal in the case of a frequency stable damped oscillator. The frequency stable damped oscillator was proposed earlier by Popp and Li [6] in order to generate hyperbolic decay. Their model was semi-classical and could not produce a constant flux of photons. We consider quantum evolution of the associated squeezed state in their model and are able to generate hyperbolic decay along with a constant flux of photons. Our approach improves their model considerably.

Photon counters detect the presence of endogenous field as biophoton emission. Since biophoton emission is observable in various living systems ranging from bacteria to human tissues [1], one can conclude that all living systems have an associated electromagnetic field. The classical field cannot show the two earlier mentioned characteristics of a biophoton signal. This motivates us to explore the possibility of biophoton field with non classical nature [12].

Coherent and squeezed states [13,14] of radiation are typical examples of a field with non-classical nature. The expectation value of the photon number operator in a coherent state of the electromagnetic field is non-zero and time independent. A detector will find a constant photon flux in such a field. The observed photon signal will not exhibit any decay or relaxation behaviour. In contrast, the field in a squeezed state exhibits relaxation behaviour. The relaxation behaviour arises from the quantum evolution of the field and in general it will not be exponential in character. The nature of the relaxation will be determined by the interaction of the field with the biological system. In the absence of the explicit knowledge of the form of this interaction, we assume that the state of the field and its evolution is given by a damped oscillator.

The dynamics of the field in a squeezed state will be represented by the Hamiltonian of a damped oscillator with time dependent frequency and mass terms. The state maintains its squeezed character during evolution. Many different forms of Hamiltonian are allowed. The relaxation behaviour is different for different Hamiltonians. We shall calculate the relaxation behaviour for the Hamiltonian of a frequency stable damped oscillator suggested by Popp and Li [16]. This form of Hamiltonian reproduces the two characteristics of biophoton emission.

The presence of a quantum field in a living system is desirable for model building. Such a field may be responsible for the long range spatio-temporal coherence and co-operative behaviour of living systems [6]. The uncertainty in either of the two canonical conjugate variables [14] in a squeezed state can be chosen over a wide range of values. One can adjust the degree of coherence and the extent of delocalization of the field. Further, the uncertainty in one variable can be made very small. As a result, squeezed state is more suitable for signal communication and information transfer. If the biophoton field has some role in signal communication, then the field in a squeezed state could result from evolutionary selection.

The specific quantum state of the field depends upon endogenous and exogenous factors. External light is an exogenous factor. It can stimulate most living systems by altering the state of their associated biophoton field. The quantum evolution of the altered field is different, so that the stimulated system shows a change in the pattern of photon emission. It is nothing but light induced biophoton emission. One can calculate the time dependence of various measurable quantities. The expectation value of the photon number operator [18] gives the intensity of the field. The relaxation behaviour of the field is obtained by calculating the time dependence of this expectation value. The leading contribution to the intensity has two terms. One term is time independent and the other has a decaying non-exponential time dependence. The time independent term is responsible for spontaneous biophoton emission, whereas the time dependent term represents the relaxation behaviour. The relative strength of the two terms varies from system to system and depends upon physiological and environmental conditions. The uncertainty product of photon and momentum operators is also calculated by us in the model. The field comes out to be very close to a minimum uncertainty packet and shows only a small attenuation in time. We have determined the variance of photon number to learn about the nature of photo count statistics. As an illustration, the model is applied to our measurements of light induced ultra weak photon emission in the flowers of *Tagetes Patula* and the damping parameter for the system is estimated.

2. Mathematical formulation of the model

A single mode free electromagnetic field of frequency ω is described by the harmonic oscillator Hamiltonian:

$$H_0 = \tfrac{1}{2}\omega^2 x^2 + \tfrac{1}{2}p_x^2, \tag{1}$$

where x and p_x are canonically conjugate position and momentum variables related to electric and magnetic field components. The classical equation of motion is

$$\frac{d^2x}{dt^2} + \omega^2 x = 0. \tag{2}$$

The system on quantization gives creation operator a^+ and annihilation operator a of the photon. Measurable quantities are expressed with these operators, e.g. photon number by the operator a^+a. The quantum state of the field can be represented by the eigen states of different operators. Number states, coherent states and squeezed states (also called two photon coherent states) are eigen states of the operators a^+a, a and b respectively. The operator b is related to operators a and a^+ by [19]

$$b = \mu a + \nu a^+, \tag{3}$$

where μ and ν are arbitrary parameters satisfying the constraint

$$|\mu|^2 - |\nu|^2 = 1. \tag{4}$$

All pairs of (μ,ν) introduced subsequently in the paper will satisfy Eq. (4). The transformation from (a^+, a) to (b^+, b) is a unitary transformation and preserves the commutation relation $[a, a^+] = [b, b^+] = 1$. Consequently, one can visualise states of quasi particles. A quasi particle is annihilated by the operator b and is created by the operator b^+. Eq. (3) can be inverted and it gives:

$$a = \mu^* b - \nu b^+. \tag{5}$$

A squeezed state of the photon will be represented by $|\beta, \mu, \nu\rangle$. It is an eigen state of the quasi particle operator with the complex eigen value β. The expectation value of the measurable quantities in the squeezed state can be calculated with the help of Eq. (5). We give below the values of photon number $\langle n \rangle$, uncertainty product $\Delta x \Delta p_x$ and $Q = \langle \Delta n^2 \rangle - \langle n \rangle$ as [19,20]

$$\langle n \rangle = |v|^2 + |\mu^* \beta - v \beta^*|^2. \tag{6}$$

$$\Delta x \Delta p_x = \frac{\hbar}{2} \sqrt{|\mu + v||\mu - v|} \tag{7}$$

and

$$Q = 2|v|^4 + |v|^2 + 2|\beta|^2(4|v|^2 + 3)|v|^2 - 2\,\mathrm{Re}(\beta^{*2}\mu v)(4|v|^2 + 1). \tag{8}$$

Pedrosa [21] has shown that coherent states of an oscillator with time dependent damping and mass term, are equivalent to the squeezed states of the free oscillator. The dynamics of a time dependent harmonic oscillator is governed by the following equation [17]

$$\frac{\mathrm{d}^2 q}{\mathrm{d}t^2} + 2\lambda(t)\frac{\mathrm{d}q}{\mathrm{d}t} + \omega^2(t) q = 0. \tag{9}$$

where q is a position variable, $\lambda(t)$ a time dependent damping coefficient and $\omega(t)$ is a time dependent frequency term. The system has a quasi particle interpretation on quantization. It is similar to the free field description in which photons are replaced by quasi particles. The quasi particle operators $b(t)$ and $b^+(t)$ are time dependent and determined [17] by the solution of Eq. (9). Eq. (9) also determines the evolution of a state. It is such that an eigen state of the time dependent operator $b(t)$ continues to remain in its eigen state with the same eigen value [17]. It resembles the evolution in a undamped oscillator, where a coherent state remains a coherent state with the same eigen value during evolution [19]. Operators $b(t)$ and $b^+(t)$ are related to photon operators by a linear unitary transformation. As a result, a coherent state of the quasi particle is also a squeezed state of the photon. A squeezed state of the photon evolves into another squeezed state in the dynamics given by Eq. (9).

Damping usually alters the mode frequency. If damping is time dependent, then the frequency also varies with time. Variable frequency is not desirable if one hopes to assign a role to biophotons [1,2] in signal communication and in maintaining the biological integrity of the system. One, therefore, imposes the requirement of frequency stability. It is achieved by taking [16]

$$\lambda(t) = \frac{\lambda_0}{(1 + \lambda_0 t)}. \tag{10}$$

where λ_0 is an arbitrary real constant. It gives the damping coefficient at $t = 0$. The Hamiltonian of the system for any stable frequency ω now becomes

$$H = \frac{p^2}{2(1+\lambda_0 t)^2} + \tfrac{1}{2}(1+\lambda_0 t)^2\omega^2 q^2. \tag{11}$$

The solution of Eq. (9) for the above damping is easily obtained. Following Jannussis and Bartzis [17] we express the quasi particle operator $b(t)$ in terms of the quasi particle operators at $t=0$. It gives

$$b(t) = \mu(t)b(0) + \nu(t)b^+(0) \tag{12}$$

with

$$\mu(t) = \cos\omega t + \frac{\lambda_0}{2\omega}\frac{\lambda_0 t}{2\omega(1+\lambda_0 t)}\sin\omega t + i\frac{\lambda_0}{2\omega}\frac{\lambda_0 t}{(1+\lambda_0 t)}\cos\omega t - i\left\{1 + \frac{\lambda_0^2}{2\omega^2(1+\lambda_0 t)}\right\}\sin\omega t \tag{13}$$

and

$$\nu(t) = \frac{\lambda_0}{2\omega}\left\{1 + \frac{1}{(1+\lambda_0 t)}\right\}\sin\omega t + i\frac{\lambda_0}{2\omega}\frac{\lambda_0 t}{(1+\lambda_0 t)}\cos\omega t - i\frac{\lambda_0^2}{2\omega^2(1+\lambda_0 t)}\sin\omega t. \tag{14}$$

The state of the field at $t=0$ is an eigen state of a quasi particle operator $b(0)$ and contains information about the living system and its environment. If the field at $t=0$ is taken to be in a state $|\beta,\mu_0,\nu_0\rangle$ with β,μ_0, and ν_0 as input parameters, then

$$b(0) = \mu_0 a + \nu_0 a^+. \tag{15}$$

The state $|\beta,\mu_0,\nu_0\rangle$ will evolve [19] into another state $|\beta,\mu_t,\nu_t\rangle e^{i\Phi(t)}$. Since the phase $\Phi(t)$ of the state does not enter our calculations it need not be determined. We can determine the parameters μ_t and ν_t by noting that the quasi particle operator $b(t)$ of the evolved state is given by

$$b(t) = \mu_t a + \nu_t a^+. \tag{16}$$

Substituting Eq. (15) into Eq. (12) we obtain μ_t and ν_t as

$$\mu_t = \mu(t)\mu_0 + \nu(t)\nu_0^* \tag{17}$$

and

$$\nu_t = \mu(t)\nu_0 + \nu(t)\mu_0^*. \tag{18}$$

The evolved state is an eigen state of operator $b(t)$

$$b(t)|\beta,\mu_t,\nu_t\rangle = \beta|\beta,\mu_t,\nu_t\rangle. \tag{19}$$

(Eqs. (12)–(19)) is used in calculating measurable quantities. The relaxation behaviour of the field is obtained by calculating the time dependence of the expectation value of the photon number operator in the state of the field. The expectation value is given by

$$\langle a^+ a\rangle = \langle \beta, \mu_t, \nu_t | a^+ a | \beta, \nu_t, \mu_t\rangle. \tag{20}$$

The right-hand side of Eq. (20) is evaluated by first inverting Eq. (16) and then using commutation relations and Eq. (19). The result has non-oscillatory as well as oscillatory time dependence. The non-oscillatory part determines the relaxation or decay behaviour. It has terms of the forms $(1+\lambda_0 t)^{-1}$ and $(1+\lambda_0 t)^{-2}$. The oscillatory part occurs with frequency ω and is too fast to be observed. It is averaged out by integrating the expression over a time interval $2\pi/\omega$. The variation of $(1+\lambda_0 t)$ during integration over the interval $2\pi/\omega$ can be ignored beyond $t \gg 1/\omega$. This condition is satisfied in biophoton emission where the frequency is in the optical range ($\omega \approx 10^{15}\mathrm{s}^{-1}$) and measurements are made beyond $t = 1$ ms [22]. The expectation value $\langle a^+ a\rangle$ averaged over the fast mode gives the number of photons $n(t)$ detected at time t as

$$n(t) = B_0 + \frac{B_1}{1+\lambda_0 t} + \frac{B_2}{(1+\lambda_0 t)^2}. \tag{21}$$

The coefficients B_0, B_1, and B_2 are explicit expressions of λ_0 and parameters β, μ_0 and ν_0. The parameters are situation specific and may depend upon many factors. The values of the coefficients may change from experiment to experiment. Since we are unable either to prepare or choose a system with its field in a known squeezed state, it is difficult to extract meaningful information about the system from these coefficients. In contrast, λ_0 is insensitive to the state of the field and is a stable quantity. It may provide significant information about the system. The data should be analysed to estimate its value.

λ_0 can be determined from the measurements of $n(t)$ provided it is less than $10^6\ \mathrm{s}^{-1}$. This restriction arises because for $\lambda_0 > 10^6\mathrm{s}^{-1}$ and $t > 1$ ms, one can replace $(1+\lambda_0 t)$ by $\lambda_0 t$ and can absorb λ_0 in the coefficients B_1 and B_2. The error in the replacement is less than 0.1%. Besides, the system will relax very quickly for large values of λ_0 and one will observe only a constant flux given by the contribution of B_0. If $\lambda_0 < 10^6\mathrm{s}^{-1}$, then one can construct a dimensionless parameter λ_0/ω which is less than 10^{-9}. It can be used as an expansion parameter. The expansion of Eq. (21) in this parameter has terms upto fourth order only, i.e.

$$n(t) = \sum_{m=0}^{4} C_m \left(\frac{\lambda_0}{\omega}\right)^m. \tag{22}$$

In the above equation, only the term C_0 is significant due to small value of expansion parameter. It is given by

$$C_0 = |\nu_0|^2 + |\beta|^2\left(1 + 2|\nu_0|^2\right). \tag{23}$$

It is independent of t and produces a constant flux of photons. C_0 gives a dominant contribution to $n(t)$ provided $|v_0| > \lambda_0/\omega$ or $|\beta| > \lambda_0/\omega$. However, if both $|v_0|$ and $|\beta|$ become of the order of λ_0/ω, then the expansion terms in Eq. (22) need to be rearranged. The rearranged expansion is given by

$$n(t) = |v_0|^2 + |\beta|^2 + \frac{\lambda_0}{\omega}\,\mathrm{Im}(\mu_0\, v_0) + \frac{\lambda_0^2}{4\omega^2}\left(1 + \frac{1}{(1+\lambda_0 t)^2}\right) + \mathrm{O}\left(\frac{\lambda_0}{\omega}\right)^3. \tag{24}$$

Eq. (24) gives leading order contributions to the three coefficients of Eq. (21). B_0 and B_2 are non-vanishing but B_1 vanishes in the expansion upto the order $(\lambda_0/\omega)^2$.

We point out that Eq. (24) is the only observable decay behaviour of the biophoton field in our model. It has a $(1+\lambda_0 t)^{-2}$ term along with a constant rate of photon emission. The strengths of decaying and constant terms depend upon the choice of parameters. For example if $\mu_0 \cong 1, v_0 = -i\lambda_0/(2\omega)$ and $\beta = 0$, then the constant component of the flux becomes zero. Similarly for the choice $\mu_0 = 1$, $v_0 = 0$ and β arbitrary, the contribution of constant terms is never less than the contribution of the decaying terms. In this choice the state of the field at $t = 0$ is a coherent state of the photon. Eqs. (23) and (24) can be combined in a single formula for phenomenological analysis. It gives $n(t)$ as

$$n(t) = B_0 + \frac{B_2}{(1+\lambda_0 t)^2}. \tag{25}$$

Gu [3] has also obtained similar expression in an exciplex model after several approximations. Our approach is much simpler and tractable.

The uncertainty product is calculated using Eq. (7). We give the result for the field initially in a coherent state evolving into a squeezed state. It has $v_0 = 0$ and gives

$$\Delta x\, \Delta p_x = \frac{\hbar}{2}\sqrt{1 + \omega(t)^2}, \tag{26}$$

where

$$\begin{aligned}\Omega(t) = {} & \frac{\lambda_0}{\omega}\left\{1 + \frac{\lambda_0^2}{2\omega^2(1+\lambda_0 t)^2}\right\} \\ & - \frac{\lambda_0}{\omega}\cos 2\omega t\left\{\frac{1}{(1+\lambda_0 t)} + \frac{\lambda_0^2}{2\omega^2(1+\lambda_0 t)^2}\right\} \\ & - \frac{\lambda_0^2}{2\omega^2}\sin 2\omega t\left\{\frac{2}{(1+\lambda_0 t)} + \frac{1}{(1+\lambda_0 t)^2}\right\}.\end{aligned} \tag{27}$$

The oscillatory behaviour has not been integrated out in the above expression. The contribution of $\Omega(t)$ is very small for $\lambda_0/\omega \ll 1$. The uncertainty product of the packet does not grow with time and it remains nearly a minimum uncertainty packet. It does not suffer appreciable attenuation due to quantum evolution. It can, therefore, be used for efficient signal transmission and communication [15,19]. The behaviour of the uncertainty product for the field initially in a squeezed state ($v_0 \neq 0$) is given by a more complicated expression but is similar to the case $v_0 = 0$. We have also determined the nature of photon statistics by calculating Q with the help of Eq. (8). Q is non-zero but small. It indicates that the distribution is not strictly Poissonian. However, the deviations are small.

3. Results and discussions

Eq. (25) is our main result which explains the two distinct types of biophoton emission in a unified framework. Eq. (25) has three unknown parameters. One parameter (B_0 or B_2) is fixed by the normalisation of the data.This leaves us with only two free parameters λ_0 and B_2/B_0 to fit the experimental data. It is valid for every biological system. As a result, gross features of biophoton emission in all systems are similar.

The model predicts a constant flux of biophotons in time for $t \ll \lambda_0^{-1}$ or $B_0 \gg B_2$. This is an important feature of our model. It has not been predicted so far. All biological systems exhibit this feature of constant flux in spontaneous biophoton emission. Energy emitted in biophoton emission is supplied by the metabolic activities of the system. The mechanism of energy transfer from the living system to its field is unknown. We have modelled only a part of the Hamiltonian that gives the evolution of the electromagnetic field. This part has an explicit time dependence and it alone cannot conserve energy. Energy conservation is ensured by the living system as a whole, which is responsible for the existence of the field in a squeezed state.

The model contains a relaxation behaviour of the from $(1 + \lambda_0 t)^{-2}$ for $B_2 \gg B_0$. This is the only form of relaxation behaviour occurring in our model. Such behaviour was observed in numerous systems [3,6,22,23]. These observations led to the idea of frequency stable damped oscillator initially in a classical model [16]. We have borrowed the form of damping and formulated a quantum mechanical framework for understanding biophoton emission. The framework correctly gives the observed decay behaviour. It may be noted that a non exponential decay rules out the origin of the biophoton from uncorrelated excited states of subsystems or from chemical reactions.

The parameters B_0 and B_2 depend upon the quantum state of the field and are holistic in character. They need not be extensive variables. They depend upon physiological and environmental factors. The dependence has not been quantified so far. Changes in biophoton signal with physiological or environmental conditions have been observed [23]. Our model attributes these changes to the values of B_0 and B_2. The detailed shape of the biophoton signal is, therefore, situation specific. This is a unique feature of our model and it offers a possibility to use the biophoton signal as a tool in extracting information about physiological and environmental factors affecting the system. Using the biophoton signal it may be possible to discriminate among biological samples (carrot, milk, egg, etc.) produced or reared under different conditions from the same species or stock, where chemical or biochemical techniques fail to differentiate [24].

As an illustration, we fit in our model the light induced biophoton emission data measured by us in a non-photosynthetic system namely, flower of *Tagetes Patula*. Nine flowers varying in colour and size were plucked randomly from different plants. The light induced photon emission was measured continuously for 200 s in the Photon Image Acquisition System (PIAS, HAMAMATSU). The details of the experimental set up and actual procedure have been described elsewhere [8]. The signal became very weak after 200 s and approached the regime of constant flux. The measurements were repeated after every hour for 6 h and subsequently once a day for next seven days. We measured the relaxation behaviour of each flower 14 times, spread over 8 days and obtained a total of 126 different sets of data. The data of each set was analysed assuming a single exponential decay, double exponential decay and our model (Eq. (25)). The parameters in different models were determined by minimising the chi square, χ^2, function. A single exponential decay gave a large value of chi square and could not reproduce the shape of the signal. A single exponential decay cannot represent the biophotonic signal. The decay with two exponentials was parametrized by

$$n(t) = E_1 \exp(-\lambda_1 t) + E_2 \exp(-\lambda_2 t), \tag{28}$$

where E_1, E_2, λ_1 and λ_2 are constants. Both Eqs. (25) and (28) are able to reproduce the shape of the signal and gave similar values for chi square. Chi square per degree of freedom was around 1.2 in various sets of data. The values of B_0 were small and negligible. The values of the coefficients E_1, E_2 and B_2 were different for different flowers. Even for the same flowers the values of these coefficients decreased with time. The decrease indicated degradation of flower after plucking. The values decreased by two orders of magnitude in eight days. Perhaps, they can be used to estimate the amount of degradation of the system. One expects the λ to be constant. The data from 126 decays gave $\lambda_0 = (0.040 \pm 0.011)\ \mathrm{s}^{-1}$, $\lambda_1 = (0.080 \pm 0.041)\ \mathrm{s}^{-1}$ and $\lambda_2 = (0.015 \pm 0.003)\ \mathrm{s}^{-1}$. The term corresponding to λ_1 is dominant in the two exponential decay model but we obtained a significantly larger standard deviation in its determination. The values of λ_0 and λ_2 were distributed normally, but the values of λ_1 were not. It suggests that Eq. (28) may simply be a parametric fit while Eq. (25) has deeper significance.

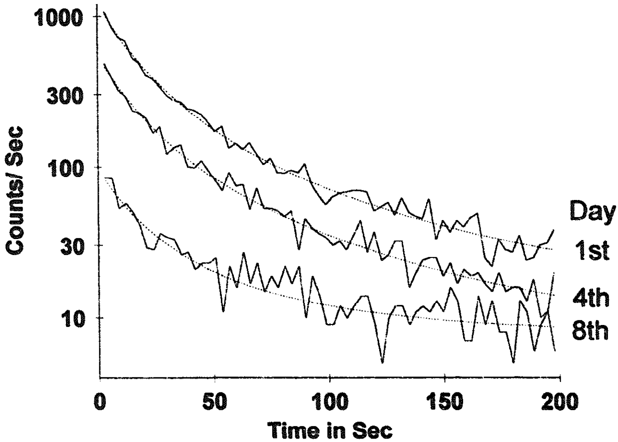

Fig. 1. Relaxation behaviour in the light induced emission from a flower of *Tagetes Patula*.

The quality of our fit is indicated in three representative cases in Fig. 1. The number of photons detected in each second is plotted as a function of time elapsed after 10 s exposure of the flower to white light. Photon counts were measured every 3 s. Observed points are joined by continuous lines. Predictions of the model are depicted by dotted curves. The flower was plucked from a plant and kept in a sample holder inside the laboratory. The three cases correspond to the measurements with the same flower on the first, fourth and eighth day of plucking. The data are well reproduced in these cases in our model. It is also true for all other sets of data. Agreement of the data in our model is particularly good for fresh flowers emanating a strong signal. Deviations are pronounced in weaker signals where the signal to noise ratio is less than 2. Our model correctly reproduces the shape of the signal even after the decrease in its strength by two orders of magnitude due to natural degradation.

The model proposes a new framework to represent and explain biophoton emission data. We feel that the earlier data showing non-exponential decay should be re-examined in this framework and future experiments should be planned to determine the dependence of the coefficients of the model on physiological and environmental factors.

Non-classical nature of biophotonic light is an important assumption of the model. It can be established by determining photo count statistics and by performing photon correlation experiments. Photo count statistics was determined in the region of constant flux in a few systems. The distribution was non-thermal and mostly Poissonian [6]. We have also measured the probability of zero photon emission for a time interval ranging from 10 μs to 10 ms in light induced biophoton emission from photosynthetic systems [25]. The measuring conditions were arranged in such a way that the difference in the predictions of thermal and Poissonian distribution was maximised. Our data agree with the prediction of Poissonian distribution. The results are unpublished so far. The results of both measurements require a non-classical nature of the biophoton field. We thus have three different types of measurements performed on different systems using different detectors indicating the existence of non-classical light. Perhaps, the biophoton field is indeed in a squeezed state of light.

References

[1] B. Ruth, in: F.A. Popp, U. Warnke, H.L. Koenig, W. Peschka (Eds.), Electromagnetic Bioinformation, Urban and Schwarzenberg, Munich, 1989, pp. 128–143.
[2] F.A. Popp, in: F.A. Popp, U. Warnke, H.L. Koenig, W. Peschka (Eds.), Electromagnetic Bioinformation, Urban and Schwarzenberg, Munich, 1989, pp. 144–167.
[3] Q. Gu, in: F.A. Popp, K.H. Li, Q. Gu (Eds.), Recent Advances in Biophoton Research and its Applications, World Scientific, Singapore, 1992, pp. 59–112.
[4] J. Slawinski, Experientia 44 (1988) 559.
[5] P.A. Jursinic, in: J.A. Govindji, D.A. Frog (Eds.), Light Emission by Plants and Bacteria, Academic Press, New York, 1986, pp. 291.
[6] F.A. Popp, in: F.A. Popp, K.H. Li, Q. Gu (Eds.), Recent Advances in Biophoton Research and its Applications, World Scientific, Singapore, 1992, pp. 1–46.
[7] W.B. Chwirot, Experientia 44 (1988) 594.
[8] R.P. Bajpai, P.K. Bajpai, J. Biolum. Chemilum. 7 (1992) 117.
[9] J. Lavorel, in: R. Govindjee (Ed.), Bioenergetics of Photosynthesis, Academic Press, New York, 1975, pp. 225.
[10] B.G. Mathew, S. Kumar, Experientia 48 (1992) 309.
[11] Q. Gu, F.A. Popp, Experientia 48 (1992) 1069.
[12] K.H. Li, in: F.A. Popp, K.H. Li, Q. Gu (Eds.), Recent Advances in Biophoton Research and its Applications, World Scientific, Singapore, 1992, pp. 113–155.
[13] J.N. Hollenhorst, Phys. Rev. D 19 (1979) 1669.
[14] D.F. Walls, Nature 306 (1983) 141.
[15] H.P. Yuen, J. Shapiro, IEEE Trans. Inform. Theo. IT26 (1980) 78.
[16] F.A. Popp, K.H. Li, Internat. J. Theoret. Phys. 32 (1993) 1573.
[17] A. Jannussis, V. Bartzis, Nuovo Cimento 102B (1988) 33.
[18] R.J. Glauber, Phys. Rev. 131 (1963) 2766.
[19] H.P. Yuen, Phys. Rev. A 13 (1976) 2226.
[20] L. Mandel, Opt. Commun. 42 (1982) 437.
[21] I.A. Pedrosa, Phys. Rev. D 36 (1987) 1279.
[22] F. Musumeci, M. Godlewski, F.A. Popp, M.W. Ho, in: F.A. Popp, K.H. Li, Q. Gu (Eds.), Recent Advances in Biophoton Research and its Applications, World Scientific, Singapore, 1992, pp. 327–344.
[23] F.A. Popp, Q. Gu, K.H. Li, Mod. Phys. Lett. B 8 (1994) 1269.
[24] K. Lambing, in: F.A. Popp, K.H. Li, Q. Gu (Eds.), Recent Advances in Biophoton Research and its Applications, World Scientific, Singapore, 1992, pp. 393–413.
[25] R.P. Bajpai, Coherent nature of photon in delayed luminescence of leaves, submitted.