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Evidence of non-classical (squeezed) light in biological systems

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Abstract

By use of coincidence measurements on "ultraweak" photon emission, the photocount statistics (PCS) of artificial visible light turns out to follow—as expected—super-Poissonian PCS. Biophotons, originating from spontaneous or light-induced living systems, display super-Poissonian, Poissonian and even sub-Poissonian PCS. This result shows the first time evidence of non-classical (squeezed) light in living tissues. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Gurwitsch was the first in 1922 to show evidence of a weak but permanent photon emission of a few counts/(s cm^2) in the optical range from biological systems, pointing out that it stimulates cell divisions [1]. After periods of neglect and even disregard, small groups in Russia, Australia, China, Italy, Japan, Germany, Poland, and the USA rediscovered "ultraweak light emission" from living tissues by use of modern photomultiplier techniques, after the second world war [2]. While there is now agreement about the universality of this effect for all living systems, no agreement has been achieved in the area of interpretation. Most of these groups believe that this spontaneous photon emission originates from radical reactions within the cells, but proof for that is still lacking. A group of German physicists, starting in 1972 at the University Marburg, followed an opposite hypothesis, i.e., that "biophoton emission" as subject of quantum optics has to be assigned to a coherent photon field within the living system, responsible for intra- and intercellular communication and regulation of biological functions such as biochemical activities, cell growth and differentiation [3]. In order to examine this hypothesis, consider that it has been shown [3,4] that biophoton emission can be traced back to DNA as the most likely candidate for working as the (main) source, and that delayed luminescence (DL), which is the long-term afterglow of living systems after exposure to external light illumination, corresponds to excited states of the biophoton field. When they relax in darkness continuously into the quasi-stationary states of biophoton emission, DL follows a hyperbolic-like

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relaxation function rather than an exponential one, indicating under ergodic conditions a fully coherent field [5,6], and that both DL and biophoton emission display identical spectral distribution. They have in common the Poissonian photocount statistics (PCS), at least down to preset time intervals as low as 10^{-5} s.

In addition, all the correlations between DL or biophoton emission and biological functions such as cell growth, cell differentiation, biological rhythms, and cancer development, turned out to be consistent with the coherence hypothesis but could be only rather poorly explained in terms of radical reactions.

However, as soon as it became more and more likely that living systems are governed by coherent states (at least of the biophoton field), the idea came up that not only coherent states but also squeezed states may play a role in biological regulation [7]. This is a consequent and progressive conclusion since biological "optimization" may make use of quantum effects just in the "ultraweak" range of intensities where squeezed states can exist at all. They are to some extent derivatives of coherent states in the "low level" region of photon numbers. In this Letter, we show experimental evidence of squeezed states in living systems using the same methods as for registering photocount statistics.

2. Materials and methods

In a dark chamber two photomultipliers (EMI 9558 QA, selected types, PM 1 and PM 2) cooled down to −30°C work as two independent detectors, channels 1 and 2. The radiating source is placed in a position that both multipliers record about the same count rate of emitted photons (Fig. 1). The details of the techniques have been described elsewhere [8,9].

The photon counts in the two channels are always recorded during a preset time interval Δt. At the same time the coincidence rate of photons between channels 1 and 2 is registered according to the principle of Fig. 2. As soon as a single event in the counter channel (say channel 1) is registered, an electronic gate is opened and—after a small delay time τ—every count of the reference channel (say channel 2) is registered as a coincident count if it happens between τ and $\tau + \Delta\tau$, where τ and $\tau + \Delta\tau$ are both small compared to Δt. More details about the equipment have been described elsewhere [8,9].

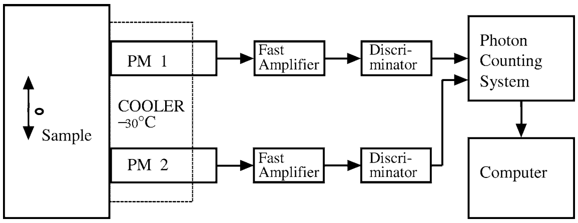


Fig. 1. Two-channel photon counting system.

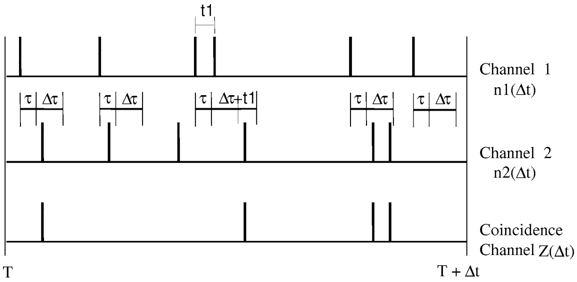


Fig. 2. The registration of coincident counts depending on the counts in the two channels.

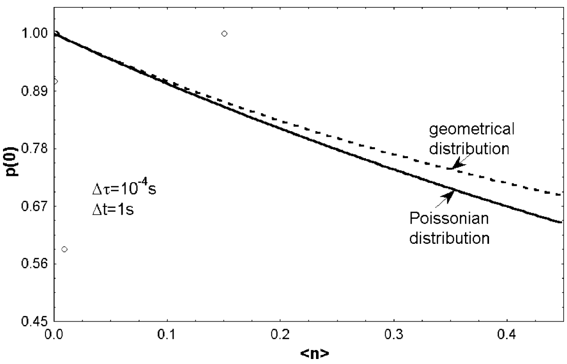
The number of coincidences in the preset time interval Δt is then

$$Z(\Delta t) = n_2 \Delta t\big(1 - \tau/(\tau + \Delta\tau)\big)\big(1 - p(0, \Delta\tau)\big), \quad (1)$$

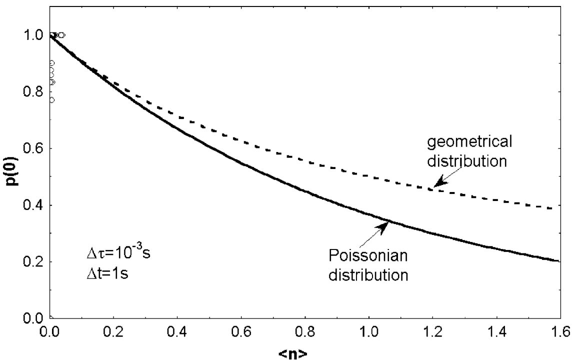
where n_2 is the number of counts in the reference channel during the time $\Delta t(1 - \tau/(\tau + \Delta\tau))$, where the gate is open, and $p(0, \Delta\tau)$ is the time average probability over Δt of measuring no photon in channel 1 always within the time interval $\Delta\tau$. Since Z and n_2 are known, the method allows us to measure $p(0, \Delta\tau)$ with high accuracy.

It is evident from (1) that $1 - p(0, \Delta\tau)$ takes the value 1 at too high intensities of the source and takes the value zero for $\Delta\tau = 0$. At the same time, if τ is of the order $\Delta\tau$, the coincidence rate gets much smaller than for $\tau \ll \Delta\tau$. We select a value $\tau = 10^{-5}$ s, in order to avoid coincidences by rescattering or afterglow effects from the dark chamber, $\Delta\tau$ is chosen around the order of $1/\dot{n}$, where $\dot{n}$ is the intensity of the weak photon source (1–10^4 counts/s) such that the effect of τ on the coincidence rate can be neglected throughout this Letter.

Figs. 3(a) and (b) show a typical measurement of the dark count rate of 10 counts/s, where $p(0) =$



(a)



(b)

Fig. 3. (a) Photocount statistics ($p(0), \Delta\tau$) of the noise of the equipment. The random coincidences are due to instabilities of the equipment. $\Delta\tau = 10^{-4}$ s. (b) Same as (a), but $\Delta\tau = 10^{-3}$ s.

$1 - Z(\Delta t)/\dot{n}_2\Delta t$ has been plotted in dependency on $\dot{n}_1(\Delta\tau)$.

In order to evaluate $p(0, \Delta\tau)$ from quantum optics and to compare it with the experimental results, let us briefly summarize the essential steps [10].

By introduction of the creation operator a^+ and the annihilation operator a which satisfy for photons the boson communication relations

$$[a, a] = [a^+, a^+] = 0, \qquad [a, a^+] = 1, \tag{2}$$

we have for number states $|n\rangle$,

$$a^+a|n\rangle = n|n\rangle, \tag{3}$$

where n is the photon number.

Using the displacement operator

$$D(\alpha) = \exp(\alpha a^+ - \alpha^* a) \tag{4}$$

and the squeeze operator

$$S(r) = \exp\left(\frac{1}{2}r\left(a^2 - (a^+)^2\right)\right) \tag{5}$$

for real r, one can generate the states

$$|\alpha, r\rangle = D(\alpha)S(r)|0\rangle, \tag{6}$$

where $|0\rangle$ is the vacuum state of a.

These states are called coherent states for $r = 0$ and squeezed states for $r \neq 0$.

The expectation values of photon numbers n in these states are

$$\langle n\rangle = \langle\alpha, r|a^+a|\alpha, r\rangle. \tag{7}$$

The probability $p(n, \Delta\tau)$ of measuring n photons ($n = 0, 1, 2, \ldots$) in the fields of average number $\langle n\rangle$ is then

$$p(n) = \frac{\langle n\rangle^n}{(\langle n\rangle + 1)^{n+1}} \tag{8}$$

for chaotic fields, as long as the coherence time $T > \Delta\tau$. In case of $T \ll \Delta\tau$, $p(n)$ approaches a Poissonian distribution [11].

For coherent fields we arrive at

$$p(n) = \exp\left(-\langle n\rangle\right)\frac{\langle n\rangle^n}{n!}, \tag{9}$$

and for squeezed fields we get

$$p(n) = (n!\cosh r)^{-1}\exp\left(-\langle n\rangle\exp(2r)\right)(1 + \tanh r) \times (\tanh r)^n H_n^2\left(\frac{-\alpha\exp(r)}{\sqrt{\sinh r}}\right), \tag{10}$$

where H_n are Hermite polynomials.

In particular, for $n = 0$ we obtain

$$p(0) = \frac{1}{(\langle n\rangle + 1)} \tag{11}$$

for chaotic fields,

$$p(0) = \exp\left(-\langle n\rangle\right) \tag{12}$$

for coherent fields, and

$$p(0) = \left(\frac{1 + \tanh r}{\cosh r}\right)\exp\left(-\langle n\rangle\exp(2r)\right) \tag{13}$$

for squeezed fields.

Eqs. (11)–(13) are useful for comparing the experimental results of the coincidence measurements with the theoretical results of quantum optics in order to find out whether the field under investigation is chaotic, coherent, or squeezed.

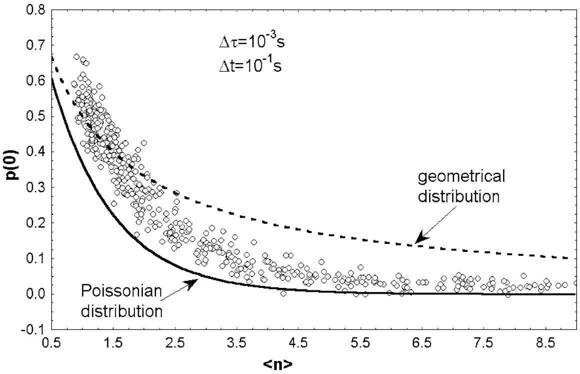


Fig. 4. $p(0)$ of a micro-lamp displays the typical photocount statistics of a classical source with a coherence time $T < \Delta\tau$.

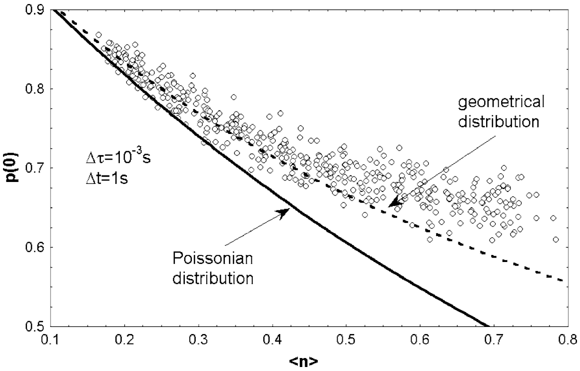


Fig. 5. $p(0)$ of a LED (Kingbright, RGB, 660 nm (GaAsP), current 0.37 µA), working at lowest level of photon emission.

3. Results and discussion

Fig. 4 displays the example of a micro-lamp (Filament lamp SLI-VCH, T1-3mm, current oscillating between 9.5 and 15.4 mA) with $T \ll \Delta\tau$. Consequently, $p(0)$ approaches a Poissonian distribution.

Fig. 5 demonstrates the validity of (11) for the case of an LED at rather low intensities of a classical light source, where $T > \Delta\tau$.

Fig. 6 shows the experimental $p(0)$ of a leaf (elderberry, *Sambucus nigra*) that has been illuminated by external light and displays delayed luminescence in darkness.

The experimental $p(0)$ never falls below the Poissonian distribution, indicating that in addition to a chaotic one, a coherent or a squeezed field (with $r < 0$) may be responsible.

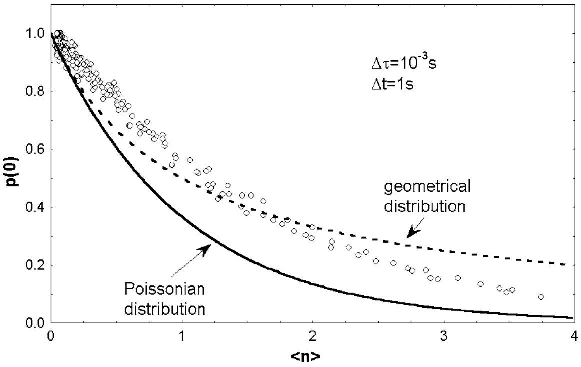


Fig. 6. Unexplained photocount statistics of a leaf which may originate from a chaotic source, a coherent or even a squeezed light field with $r < 0$.

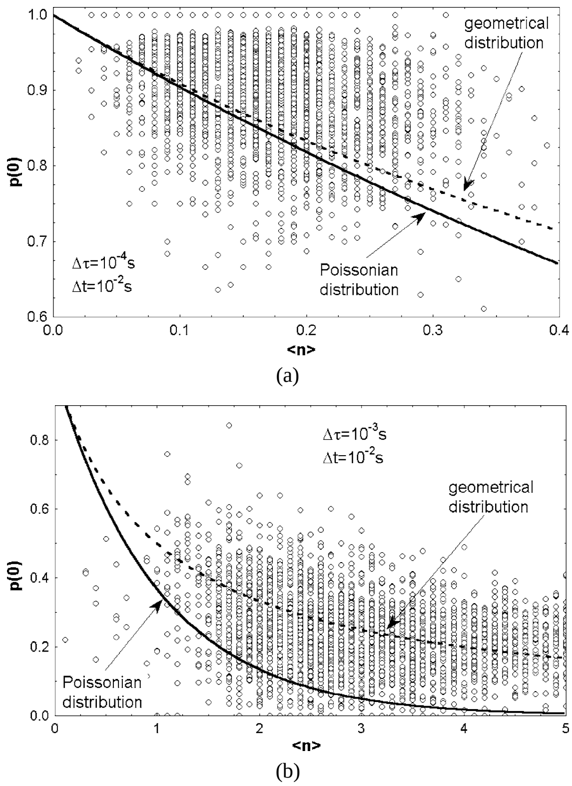
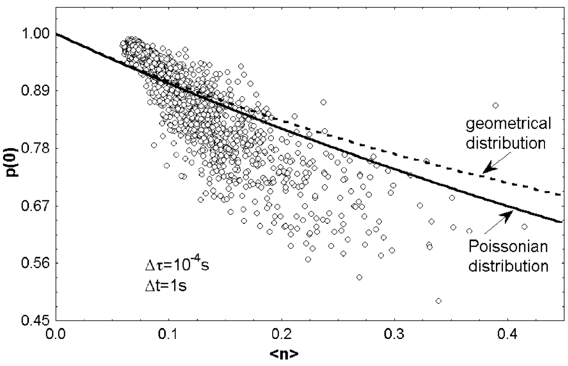
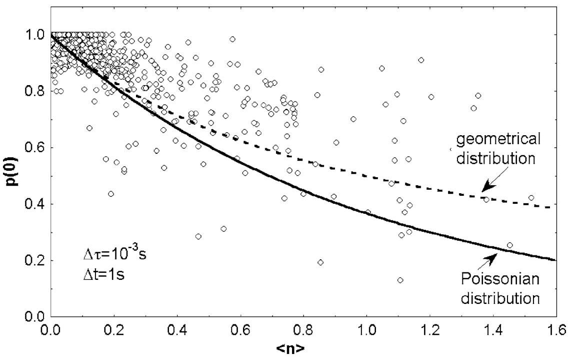


Fig. 7. (a) $p(0)$ of the photon emission of the leaf of Fig. 6 that has been illuminated by the LED of Fig. 5. $\Delta\tau = 10^{-4}$ s. (b) Same as (a), but $\Delta\tau = 10^{-3}$ s.

Figs. 7(a) and (b) demonstrate the case of the same leaf of Fig. 6 that is illuminated by the LED of Fig. 5 at the back such that only the emitted photons of



(a)



(b)

Fig. 8. (a) $p(0)$ of spontaneous light emission of *Gonyaulax polyedra*, kept under natural conditions $\Delta\tau = 10^{-4}$ s. (b) Same as (a), but $\Delta\tau = 10^{-3}$ s.

the leaf and not of the lamp hit the photomultipliers. It is evident that the experimental values $p(0)$ fall significantly below the Poissonian distribution. This is possible only for non-classical (squeezed) light with $r > 0$. It seems that states $|\alpha, r\rangle$ with $r < 0$ also take part in the photon-induced emission of the leaf.

Figs. 8(a) and (b) demonstrate that spontaneous emission of biological systems may also originate from squeezed states. The example concerns 35000 *Gonyaulax polyedra* (Dinoflagellates) at room temperature, kept in sea water in a 10 ml quartz cuvette.

All the results are compatible with the well-known results of photocount statistics as well for chaotic as for coherent and squeezed non-classical light. In no case of artificial light sources it has been found a $p(0) < \exp(-\langle n\rangle)$. The exception of random coincidences of the dark count rate are certainly due to instabilities of the equipment. They play no role for the whole investigation. On the other hand, biological systems are certainly able to emit photons following $p(0) < \exp(-\langle n\rangle)$. The only possible explanation can be given in terms of non-classical (squeezed) light, since as well chaotic, as coherent light sources or superposition of them never lead to sub-Poissonian photocount statistics.

It is worthwhile to note that this kind of investigation provides a new and most powerful tool of investigating biological tissues.

Acknowledgements

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