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Review

Biophotons, coherence and photocount statistics: A critical review

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ABSTRACT

Biological samples continuously emit ultra-weak photon emission (UPE, or "biophotons") which stems from electronic excited states generated chemically during oxidative metabolism and stress. Thus, UPE can potentially serve as a method for non-invasive diagnostics of oxidative processes or, if discovered, also of other processes capable of electron excitation. While the fundamental generating mechanisms of UPE are fairly elucidated together with their approximate ranges of intensities and spectra, the statistical properties of UPE are still a highly challenging topic. Here, we review claims about nontrivial statistical properties of UPE, such as coherence and squeezed states of light. After the introduction to the necessary theory, we categorize the experimental works of all authors to those with solid, conventional interpretation and those with unconventional and even speculative interpretation. The conclusion of our review is twofold; while the phenomenon of UPE from biological systems can be considered experimentally well established, no reliable evidence for the coherence or nonclassicality of UPE has actually been achieved up to now. Furthermore, we propose perspective avenues for the research of statistical properties of biological UPE.

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1. Introduction

Ultra-weak photon emission (UPE, or "biophotons") from biological systems is a luminescent phenomenon which is present without any direct external stimulation nor additionally applied external luminophores [1]. While there is some consensus about the intensity and spectrum of UPE [1,2], claims about statistical properties of UPE are very controversial. We aim to explain and settle this controversy in this critical review.

Electronic excited states giving rise to UPE are generated chemically in the course of oxidative metabolic and stress processes [1] in biological samples and living organisms. Several other terms synonymous to ultra-weak photon emission occur in the literature: autoluminescence [3], weak luminescence [4], low level chemiluminescence [5], biophotons/biophoton emission [6,7], *etc.* The spectral range of UPE is known to lie at least in the range from 350 nm to 700 nm [2] and its intensity is up to several hundreds to one thousand photons per square centimeter per second in the entire mentioned spectral range.[1]

There have been many claims about nontrivial statistical properties of UPE since 1980s, such as coherence and even squeezed states of light [8–14]. Such properties of UPE would be of great physical and biological importance. Firstly, if the claims of UPE coherence were proved to be true, a novel mechanism of chemically powered ultra-low power lasing would be very likely discovered. Secondly, there would also be great implications in biology since coherence or squeezed states of UPE would bring an evolutionary advantage for organisms in terms of ultra-fast optical communication [15] for the purposes of intracellular and intercellular interactions and organization [16].

Optical biocommunication has been targeted by several reviews [15,17–21]. The intensity and spectral properties of UPE have also been recently reviewed [1,2]. However, there is no critical review which covers the detailed technical aspects of the statistical properties of photon emission from biological systems. Here, we present the development and current state of the literature on the statistical properties of UPE, we especially focus on coherent and squeezed states of light and provide a critical reflection of these works.

We start with the presentation of the necessary theory about photocount measurement coherence and quantum optics in Section 2 and then we review the models which are used to analyze experimental distributions of UPE photocount statistics. In Section 3, we review the experiments of statistical properties of UPE and assess them from the point of view of the current understanding of physics and biophysics. We found that although there are quite numerous papers which contain unsubstantiated claims about statistical properties of UPE, several high quality works can also be found. Based on reliable works, we propose future avenues in the research of the statistical properties of biological UPE in our conclusion.

[1] The intensity of UPE within the visible region of the spectrum is many orders of magnitude higher than the intensity of thermal radiation (described by Planck's law) for other parameters (sample area, temperature, *etc.*) being the same, see [1, Fig. 2].

2. Statistical properties of light

2.1. Theory of photocount measurement

The statistical properties of UPE were mostly investigated experimentally by measuring the distribution of counts produced by UPE in a photodetector. Therefore, we briefly introduce the classical and quantum approach to photocount distributions (*photocount statistics* is another term often used in the literature).

2.1.1. Classical theory

The intensity of the light field averaged over a cycle of the oscillation is given by the expression [22, p. 86]

$$\bar{I}(t) = \frac{1}{2}\epsilon_0 c \left| E(t) \right|^2, \tag{1}$$

where $\bar{I}(t)$ is the intensity (irradiance) averaged over a cycle of oscillation with units W/m^2, ϵ_0 is the permittivity of the vacuum, c is the velocity of light in the vacuum and $E(t)$ is the intensity of the electric field. The intensity can also be obtained as the time average of the Poynting vector perpendicular to the surface of the detector.

Let the efficiency of the detector be denoted by η. According to the semi-classical theory of optical detection [22, p. 120], there is such a probability distribution $P(W)$ that the probability $p_n(t,T)$ of detecting n photoelectric emissions in a finite time interval from t to $t+T$ is

$$p_n(t,T) = \frac{1}{n!}\left\langle W^n e^{-W} \right\rangle = \frac{1}{n!}\int_0^\infty W^n e^{-W} P(W)\, dW, \tag{2}$$

where $W = \eta\int_t^{t+T} I(\tau)\, d\tau$ is the integrated light intensity and η is a coefficient containing dimensional factors and describing the efficiency of the detector, so that W is dimensionless.

2.1.2. Quantum theory

The quantum expression for the probability that n photocounts occur between time t and $t+T$ is [23; 22, p. 276; 24, p. 725]

$$p_n(t,T) = \left\langle : \frac{\hat{W}^n}{n!} e^{-\hat{W}} : \right\rangle, \tag{3}$$

where

$$\hat{W} = \eta\epsilon_0 c \int_t^{t+T} |\hat{E}(t)|^2, \tag{4}$$

in the Heisenberg representation.

All the phenomena are basically of a quantum nature, but we say that a distribution of photocounts is classical if there exists a classical density distribution (*i.e.* a non-negative $P(W)$) such that the (quantum) probability given by Eq. (3) is equal to the classical one given by Eq. (2). The characterization of non-classical light was investigated in detail [24,25]. The probability of photocount detection is purely quantum if no such $P(W)$ exists.

2.1.3. Conditional probability

Some experiments are carried out with two photomultipliers [26, p. 87; 27, Chapter by X. Shen, p. 287]. When a photon is detected by photomultiplier 1, the photons in photomultiplier 2 are registered during the time interval Δt. Bayes' theorem tells us that the conditional