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Nontrivial quantum and quantum-like effects in biosystems: Unsolved questions and paradoxes

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ABSTRACT

Non-trivial quantum effects in biological systems are analyzed. Some unresolved issues and paradoxes related to quantum effects (Levinthal's paradox, the paradox of speed, and mechanisms of evolution) are addressed. It is concluded that the existence of non-trivial quantum effects is necessary for the functioning of living systems. In particular, it is demonstrated that classical mechanics cannot explain the stable work of the cell and any over-cell structures. The need for quantum effects is generated also by combinatorial problems of evolution. Their solution requires a priori information about the states of the evolving system, but within the framework of the classical theory it is not possible to explain mechanisms of its storage consistently. We also present essentials of so called quantum-like paradigm: sufficiently complex bio-systems process information by violating the laws of classical probability and information theory. Therefore the mathematical apparatus of quantum theory may have fruitful applications to describe behavior of bio-systems: from cells to brains, ecosystems and social systems. In quantum-like information biology it is not presumed that quantum information bio-processing is resulted from quantum physical processes in living organisms.

Special experiments to test the role of quantum mechanics in living systems are suggested. This requires a detailed study of living systems on the level of individual atoms and molecules. Such monitoring of living systems in vivo can allow the identification of the real potentials of interaction between biologically important molecules.

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1. Introduction

The idea that quantum mechanics can play an important role in the existence of life was put forward at the beginning of this science. Niels Bohr (1938) was first when he spoke about life as essentially quantum phenomena. Later, Wigner (1961) returned to this subject and suggested that consciousness must play an important role in quantum mechanics.

In recent decades, the study of non-trivial quantum effects in biological systems has received new impetus. Much of this is because technologies of working with micro-particles, individual electrons, atoms, molecules, etc., have been developed. On the other hand, quantum mechanics theory has developed also (the theory of the Zeno effect, decoherence, entanglement of quantum states, etc.).

Among the first theoretical papers devoted to quantum effects in biological systems are works of Penrose (1989), Beck and Eccles (1992), Ogryzko (1997), McFadden and Al-Khalili (1999), Igamberdiev (1993).

A number of such quantum effects are observed experimentally, although not in vivo: e.g., quantum stages of photosynthesis and magnetic orientation of birds. Other effects are largely speculative, for example, adaptive mutations, quantum effects in opening and closing of ion channels, quantum effects in microtubules, protein folding, motion of polymerases, and others.

What is commonly understood by the term “non-trivial quantum effects”? Naturally, quantum mechanics is implicit in the description of all living systems in the sense that the existence of atoms, as well as chemical reactions between them, is not possible without quantum effects. Consequently, by non-trivial quantum effects we must mean something different – quantum effects in biological systems that to some extent are surprising for their functioning. For example, if the cell as a whole demonstrated

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quantum properties, it would be a non-trivial effect because it is assumed that its behavior can be described classically.

Conversely, are quantum effects necessarily associated with the manifestation of the wave properties of particles (diffraction and interference)? The answer to this question is not obvious; for example, ferromagnetism is essentially a quantum phenomenon because classical models do not explain it. However, macroscopic ferromagnetic samples do not exhibit wave properties. Consequently, non-trivial quantum effects are more subtle, not necessarily related to interference. These ideas must be invoked when the classical explanation of any phenomenon is completely unsatisfactory. As we shall see, just these effects may play the most important role in biological systems.

However, in the study of quantum effects in biological systems a number of important questions remain:

- How important are quantum effects for living systems? Are the appropriate processes (e.g., photosynthesis) effective without non-trivial quantum effects?
- Is it possible to combine these theories on the basis of any first principles?
- Quantum effects are often associated with paradoxes (Schrödinger's cat, Wigner's friend), but paradoxes are also present in the understanding of living systems (e.g., Levinthal's paradox). The question arises whether the solutions of paradoxes (unsolved problems) in biology may be connected with quantum mechanics.

We also discuss a more general viewpoint on biological applications of the quantum formalism which based on the quantum-like paradigm*: sufficiently complex bio-systems process information by violating the laws of classical probability and information theory*. In particular, the law of total probability (the law of conservation of probability can be violated). Therefore the mathematical apparatus of quantum theory may have fruitful applications to describe behavior of bio-systems: from cells to brains, ecosystems and social systems. In quantum-like information biology it is not presumed (but neither denied) that quantum information bio-processing is resulted from quantum physical processes in living organisms. In this approach the quantum formalism is treated operationally as a calculus for probabilistic predictions about possible results of measurements. This matches well Bohr's views as well as with the information interpretation of quantum mechanics (Zeilinger-Brukner) and Quantum Bayesianism (QBism: Fuchs-Mermin-Caves-Schack). Recently quantum-like models found numerous applications in mathematical modeling of cognition and decision making, psychological behavior (including disjunction, conjunction and order effects, irrational behavior), game theory (games of the prisoners dilemma type), sociology, molecular biology, genetics (e.g., glucose-lactose metabolism in E-coli bacteria) and epigenetics, evolution theory. In such applications one of the main features of the quantum formalism is its ability to describe adaptive dynamics of biological systems, e.g., with the aid of theory of *open quantum systems*. This project is realized by rapidly growing multidisciplinary and international community (psychology, physics, mathematics, molecular biology, genetics, social and political science, economy, finances) known under the name “Quantum Interactions”, we can mention the important contributions of D. Aerts and S. Sozzo, H. Atmanspacher and T. Filk, J. Busemeyer and E. Phothos, M. Asano, I. Basieva, A. Khrennikov, M. Ohya, I. Yamato, E. Conte, E. Haven and P. Khrennikova, E. N. Dzhafarov and Kujala, J. Acacio de Barros, see chapter 4 for literature-review.

At the same time by using the formalism of complex Hilbert space for bio-systems one has to be cautious. Aforementioned violation of the law of total probability/conservation of probability is just one of features of the quantum formalism. Systems described by this formalism can violate this law, but not vice versa. Thus, although probabilistic behavior of bio-systems does not match completely with the basic laws of classical probability theory, it is not necessary quantum(-like). Other nonclassical/nonquantum probabilistic models might match better the real biological situation. In quantum-like studies we use the mathematical formalism based on complex probability amplitudes simply as the most well developed and tested nonclassical probabilistic calculus. This is purely phenomenological approach. Up to now, it works and data collected in variety of experiments, see chapter 4, can be described by complex Hilbert space theory. However, we may expect that some biological phenomena may exhibit not only violation of laws of classical, but even quantum probability theory.

Finally, we remark again that in the quantum-like modeling of bio-phenomena (in contrast to the real quantum biophysics) we do not try to assign any physical meaning to complex coefficients in states superposition. They only provide the vector space representation of the probabilistic content of states of systems. For example, consider the quantum-like approach to modeling of cell's metabolism. The latter is a process of huge complexity and its adequate representation is the nontrivial problem of system biology. However, the essentials of its probabilistic structure can be represented in quantum-like way by using a phenomenological complex Hilbert space model, see chapter 4. Of course, in such a model details of the metabolism process generating the quantum-like (at least nonclassical) structure of probabilistic behavior are ignored.

Thus, there is need for a unified framework for understanding what biological effects should be described on the basis of quantum mechanics.

This article provides an overview of non-trivial quantum effects in biological systems in the light of some unsolved problems in modern biology. Classical paradoxes that may have a quantum solution are also considered.

Ideas about the non-trivial role of quantum mechanics in living systems can be divided into the subject of studies, that is, for those components of living systems in which these effects play an important role. Accordingly, the article is organized as follows:

The first chapter is devoted to quantum effects of energy conversion in a living system. These effects include photosynthesis, protein folding, molecular recognition, and others.

The second chapter is devoted to quantum effects in the evolution of life. Most attention is given to the role of quantum mechanics in the mechanisms of evolution in terms of enumeration problems.

The third chapter is devoted to the role of quantum mechanics in the functioning of the mind and brain. Similarities and differences of quantum effects in biological systems at different levels of their organization are discussed also.

The fourth chapter is devoted to quantum information biology, its foundational background, including coupling to traditional quantum biophysics and quantum information and probability. We emphasize the novel possibilities of quantum theory to represent mathematically adaptive dynamics for biological systems.

The fifth chapter is devoted to possible experiments to test theories and to the identification of new non-trivial quantum effects.

2. Quantum effects and energy transformation in organisms

Every organism is a complex network of chemical reactions, the effective functioning of which is largely due to the transfer of electrons from one atom to another. In this sense, quantum mechanics always plays an important role in energy transmission and

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