

The question “Is life quantum?” emerges as one of the most fascinating frontiers of contemporary science. Inspired by pioneers like Erwin Schrodinger (1887-1961), whose book “What is Life?” translated in 1997 by UNESP publisher, this work laid the foundations for this investigation, seeking to understand whether quantum phenomena play fundamental roles beyond mere molecular stability of living matter. One of Erwin Schrodinger’s great contributions was demonstrating that the quantized energy levels of the hydrogen atom, previously predicted by Niels Bohr, could be obtained through Schrodinger’s equation. This equation describes the evolution of the wave function of a quantum system, such as the electron in the hydrogen atom. Thus, this work proposes to explore how quantum biology, a rapidly developing interdisciplinary field, investigates the possibility that life utilizes quantum principles to operate with unique efficiency and complexity.

The advent of quantum mechanics reformulated the physical sciences, leading to enormous advances in physics, chemistry, and computer science. In recent years, biology has made advances through interdisciplinary work with chemistry and physics. However, the impact of the quantum revolution on biology remains largely unexplored. Among the most intriguing aspects is the possible role that quantum physics plays in biology. This topic generates vigorous and lasting debate. Quantum physics undeniably sustains the existence and stability of atoms and molecules, including the macromolecules fundamental to biology. However, the question persists: does quantum physics extend its role beyond this scope, imbuing characteristics observed in living (organic) matter?

Quantum mechanics is undeniably the basis for the existence and stability of atoms and molecules, including fundamental biological macromolecules. The central question is whether its principles extend to confer specific characteristics to living matter. The very formulation of quantum mechanics involved profound debates about physical reality, whose philosophical and scientific implications continue to be relevant when studying complex biological systems. Quantum biology represents a frontier of knowledge, with the potential to transform our understanding of the most basic mechanisms of life. If quantum phenomena truly play a crucial role in biological processes, this could open new avenues for technology development, from optimizing bioenergetic processes to innovative approaches in medicine. Furthermore, exploring this intersection between physics and biology challenges established paradigms and stimulates interdisciplinary collaboration, a fundamental pillar for scientific advancement. The proposal aims to address whether biological systems employ quantum advantages and whether a complete description of biological systems requires quantum mechanics, as suggested by the contest.

Emerging evidence from theoretical and experimental physics, computational chemistry, and experimental biology suggests that certain processes in living organisms exploit quantum phenomena such as long-duration quantum coherence, entanglement, and quantum tunneling. The main phenomena investigated include photosynthesis, smell, and navigation of migratory birds. Photosynthesis, the process by which plants and some bacteria convert sunlight into chemical energy, is one of the most studied examples of biological phenomena with possible quantum influence. Research indicates that energy transport in light-harvesting complexes occurs with remarkable efficiency that cannot be fully explained by classical physics. Quantum coherence, where energy moves through multiple pathways simultaneously, appears to play a crucial role in this transport, minimizing losses and optimizing energy transfer. Macromolecules involved in photosynthesis exhibit electronic oscillations that can only be described by quantum mechanics, suggesting that light absorption leads to electronic states in superposition.

A central question is how the decoherence process is delayed in the cellular environment, and whether advances in quantum thermodynamics can help explain this. The ability to distinguish a vast range of odors with high sensitivity has traditionally been attributed to the shape of odorant molecules that fit into specific receptors. However, quantum biology proposes an alternative theory: the vibrational tunneling hypothesis. According to this theory, the nose detects not only the shape of molecules but also their specific vibrations. When an odorant molecule interacts with an olfactory receptor, electrons can perform quantum tunneling through energy barriers, generating a signal that the brain interprets as a smell. This molecular vibration would allow precise distinction between thousands of odors, even those with similar chemical structures but different vibrational patterns.

The impressive ability of migratory birds to orient themselves using Earth’s magnetic field is another phe-

nomenon where quantum mechanics may be at play. The quantum magnetoreception theory suggests that proteins in birds' eyes, called cryptochromes, are sensitive to magnetic fields. When light hits these proteins, entangled electron pairs are formed. The spin of these electrons is influenced by Earth's magnetic field, altering subsequent chemical reactions and generating electrical signals that orient the animal. This mechanism acts as a "biological quantum compass," allowing extremely precise navigation over long distances.

Beyond the examples above, quantum biology explores the possible relevance of other quantum phenomena in biological systems, such as superposition, where particles can exist in multiple states simultaneously, which could have implications in complex cellular processes. Entanglement, the interconnection of particles where the state of one instantly affects the state of another, regardless of distance, could explain coordination and efficiency in certain biological reactions. Quantum tunneling, the ability of particles to cross energy barriers even without having sufficient energy to do so, beyond smell, may be relevant in enzymatic reactions and genetic mutations. Spin, the intrinsic property of particles that can influence redox processes and be affected by magnetic fields, with possible implications in cellular response to stimuli. At a higher level, considering that biology, particularly brain physiology and the emergence of consciousness, is rooted in underlying physical interactions with quantum bases, what role does quantum physics play in understanding the brain and consciousness? This proposal will seek to explore this intriguing question.

Despite promising evidence, quantum biology faces significant challenges. The main difficulty lies in experimentally demonstrating that quantum effects are not only present but functionally relevant to biological processes, and not mere epiphenomena. The biological environment, warm and humid, is prone to decoherence, which is the loss of quantum properties due to interaction with the environment. Understanding how biological systems manage to maintain quantum coherence for sufficient time for it to be functional is a crucial research point. Another challenge is the interdisciplinary nature of the field, which requires collaboration between physicists, chemists, biologists, and computer scientists. In Brazil, for example, there are still few institutions with institutionalized programs in this area, making it difficult to train new researchers.

The future perspectives of quantum biology are vast. Deepening the understanding of these phenomena can lead to advances in various areas, such as medicine, with the development of new therapies and diagnostics based on quantum principles, such as spin manipulation to treat diseases or understanding disease mechanisms at the quantum level. In bioengineering, the creation of more efficient artificial systems for energy capture (inspired by photosynthesis) or development of biosensors with enhanced sensitivity. In quantum computing, biology can offer insights into how nature performs complex computations efficiently, inspiring new algorithms and architectures for quantum computers.

To investigate the intersection between physics and biology and answer the question "Is life quantum?", we propose a multifaceted approach that combines experimentation, theoretical modeling, and computational simulation, with emphasis on developing innovative tools, methodologies, and conceptual frameworks, and on practical application of the work. This includes experimental studies to detect and manipulate quantum states in biological systems, such as using advanced spectroscopy techniques to observe quantum coherence in proteins, or applying controlled magnetic fields to investigate magnetoreception in living organisms. New experimental approaches to address problems will be considered, as suggested by the contest. The development of theoretical models that incorporate quantum mechanics principles to describe biological processes can help predict behaviors and identify conditions under which quantum effects become relevant, including the complexity of biological systems and correlations between quantum characteristics, complexity, and entropy. The use of high-performance computational simulations to explore the behavior of biological molecules at the quantum level allows testing hypotheses and investigating scenarios that would be difficult or impossible to replicate experimentally. Fostering collaboration between physicists, chemists, biologists, and computer scientists to integrate different perspectives and knowledge, accelerating progress in the field and promoting the development of new tools and methodologies is crucial. The proposal will answer central questions inspired by FQXi guidelines, such as whether biological systems employ quantum advantages, whether a complete description of biological systems necessarily requires quantum mechanics, what role quantum physics plays in understanding the brain and consciousness, and how to define and quantify the complexity of living systems in relation to their quantum properties, and whether it is possible to develop new tools to measure correlations between quantum characteristics, complexity, and entropy in biological systems.

The question “Is life quantum?” is not only an academic curiosity but a question that can redefine our understanding of biology and pave the way for unprecedented technological innovations. Emerging evidence in photosynthesis, smell, and navigation of migratory birds suggests that quantum mechanics may be an intrinsic component of vital processes. Although the challenges are considerable, quantum biology offers an exciting perspective for unraveling the mysteries of life, revealing the elegance and complexity of the universe at its smallest scales. By embracing this new frontier, we can not only expand our scientific knowledge but also develop innovative solutions to 21st-century challenges, addressing the fundamental questions proposed by the FQxI contest. It is expected that this work will contribute to the debate about the role of quantum mechanics in biology, critically evaluating the evidence and challenges. In the end, we will answer whether life, in its essence and functioning, is intrinsically quantum, or whether the observed phenomena can be explained by classical mechanisms emerging from biological complexity. The answer could open new paths for understanding life and for developing nature-inspired technologies.