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FEATURES OF QUANTUM BIOLOGY

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Background

All living systems are made up of molecules, and fundamentally all molecules are described by quantum mechanics. Traditionally, however, the vast separation of scales between systems described by quantum mechanics and those studied in biology, as well as the seemingly different properties of inanimate and animate matter, has maintained some separation between the two bodies of knowledge. Recently, developments in experimental techniques such as ultrafast spectroscopy [1], single molecule spectroscopy [2–3], time-resolved microscopy [4–5] and single particle imaging [6–7] have enabled us to study biological dynamics on increasingly small length and time scales, revealing a variety of processes necessary for the function of the living system that depend on a delicate interplay between quantum and classical physical effects.

This article discusses the possible multifaceted applications of Quantum Physics in Plants, Insects as well as the origin of life and its importance for the human being. Quantum biology is the application of quantum theory to aspects of biology for which classical physics fails to give an accurate description. In spite of this simple definition, there remains debate over the aims and role of the field in the scientific community. This article offers a perspective on where quantum biology stands today, and identifies potential avenues for further progress in the field.

Terminology:

Quantum mechanics is the fundamental theory that describes the properties of subatomic particles, atoms, molecules, molecular assemblies and possibly beyond. Quantum mechanics operates on the nanometre and sub-nanometre scales and is at the basis of fundamental life processes such as photosynthesis, respiration and vision. In quantum mechanics, all objects

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have wave-like properties, and when they interact, quantum coherence describes the correlations between the physical quantities describing such objects due to this wave-like nature.

The world at the scale of spinning atoms and subatomic particles is governed by the probabilistic rules of quantum mechanics, which often produce effects that seem counterintuitive to organisms living in a word usually described perfectly well by more-standard physics. These effects have been harnessed for multiple technological applications, and the possible role of quantum phenomena in several biological systems is now being.

Keywords: Quantum biology, Quantum mechanics.

Entanglement: two particles are said to be quantumly entangled if their states are interdependent, regardless of the distance separating them. In the classic example of entanglement two entangled electrons, when measured, will have opposite spins. Important for, quantum computing, quantum cryptography. Studied in, photosynthesis, magnetoreception, human consciousness.

Qubits: These units of information are the quantum equivalent of standard binary digits or bits. While a bit can have a state of 0 or 1, qubits can have multiple states simultaneously, and may be entangled with other qubits to perform parallel computations. Qubits can be encoded in the spin states of electrons and other subatomic particles. Important for, quantum computing. Studied in, human consciousness.

Tunneling: Particles at the quantum scale have wave-like properties, and their exact location at any moment is described by a probabilities, traverse – or tunnel through – apparently impermeable energy batteries. Important for, thermonuclear fusion, scanning tunneling microscopy. Studied in, enzyme catalysis, photosynthesis, olfaction, DNA mutation.

Coherence: Because quantum objects can behave like waves, they can exhibit a property of waves called coherence underlies several effects observed by quantum physicists, including entanglement as well as interference patterns manifested as so-called quantum beating. Loss of coherence has traditionally been through to happen very quickly in the molecular bustle of ambient – temperature environments. Important for, lasers, superconductors, quantum computing. Studied in, photosynthesis, magnetoreception, vision, respiration.

Most ideas in quantum biology are still driven more by theory than by experimental support, but a number of researchers are now trying to close the gap. Vedral’s team plans to collect more data on bacterial entanglement later this year, and physicist Simon Gröblacher of Delft

University of Technology in the Netherlands has proposed carrying out entanglement experiments with tardigrades. In 2017, Al-Khalili and his Life on the Edge(2014)[8] coauthor, University of Surrey biologist Johnjoe McFadden, helped establish a doctoral training center for quantum biology to encourage interdisciplinary crosstalk and advance research efforts. Among the wider community of scientists and research funders, “now you’re not considered completely mad if you say you’re studying quantum mechanics in biology,” McFadden says. “It’s just considered a little bit wacky.”

During the light-harvesting reaction in plants and some microbes, photons excite electrons contained in chlorophyll molecules to create entities called excitons.

Quantum mechanics: an introduction for biologists

At the beginning of the twentieth century, the success of classical physics in describing all observable phenomena had begun to be challenged in certain respects. In 1900, as a means to explain the spectral energy distribution of blackbody radiation, Planck introduced the idea that interactions between matter and electromagnetic radiation of frequency n are quantized, occurring only in integer multiples of h*v*, where h is the fundamental Planck constant. Five years later, Einstein further developed the notion of energy quantization by extending it to include the photon, a quantum of light. This concept is illustrated by the photoelectric effect where light incident on a material leads to the emission of electrons. It is, however, not the intensity of the light that determines this emission but rather its frequency.

Even low-intensity light of a suitable frequency will lead to electrons being emitted whereas high-intensity light below this threshold frequency will have no effect. Einstein explained this by proposing that in this instance light behaves as a particle rather than a wave, with discrete energies h*v* that can be transferred to the electrons in a material. Bohr’s 1913 model of the hydrogen atom, with its discrete energy states, and Compton’s 1923 work with X-rays all contributed to the beginning of a new era in modern physics. These ways of explaining blackbody radiation and the photoelectric effect, as well as atomic stability and spectroscopy, led to the development of quantum mechanics, a theory that has proved extremely successful in predicting and describing microphysical systems [9,10].

Whereas Planck and Einstein began the quantum revolution by postulating that radiation also demonstrates particlelike behaviour, de Broglie, in 1923, made the complementary suggestion that matter itself has wave-like properties, with a wavelength related to its momentum through Planck’s constant. This hypothesis suggested that matter waves should undergo diffraction, which was subsequently proved by experiments that demonstrated that particles such as electrons showed interference patterns. Schro¨dinger built on this observation in his formulation of quantum mechanics, which describes the dynamics of microscopic systems through the use of wave mechanics. The formulation of quantum mechanics allows for the investigation of a number of important facets of a quantum state: its mathematical description at any time t, how to calculate different physical quantities associated with this state and how to describe the evolution of the state in time [9, 10].

PHOTOSYNTHESIS: ALL PATHS TRAVELED

During the light-harvesting reaction of photosynthesis in plants and some microbes, a photon excites an electron in a chlorophyll molecule to create a structure called an exciton—an entity containing both the excited electron and the positively charged hole it leaves behind. This exciton is then transferred via other chlorophyll molecules until it reaches a protein complex called the reaction center.

These excitons are then transferred from chlorophyll molecule to chlorophyll molecule until they reach the reaction center—a cluster of proteins where their energy can be captured and stored.

Excitons can lose energy as they're transferred, meaning that the more roundabout their routes are among the chlorophyll molecules, the less energy reaches the reaction center. Physicists suggested decades ago that this wastefulness could be averted if the transfer process was quantum coherent. That is, if excitons could travel like waves rather than particles, they could simultaneously try out all paths to the reaction center and take only the most efficient route.

In 2007, a team led by chemists Graham Fleming claimed to have observed quantum coherence in complexes of chlorophyll molecules extracted from green sulfur bacteria, photosynthetic microbes often found in the deep ocean where light availability is low. The researchers used a technique that analyzes the energy absorbed and emitted by a sample, and detected a signal called quantum beating—oscillations they interpreted as evidence of coherence—in complexes cooled to 77 Kelvin. Over the next few years, they and other groups replicated the results at ambient temperatures,[11] and extended the findings to chlorophyll complexes from marine algae[12] and spinach[13].

Coherence effects in photosynthesis are now a well-accepted phenomenon, says Blankenship. As is the case for tunneling in enzymes, "the most relevant discussion at this point is whether they really have an effect on [the] efficiency of the system or some other aspect of it that gives a real biological benefit. I think the jury's still out."

MAGNETORECEPTION: SPINNING SENSORS

According to the radical-pair model of avian magnetoreception, cryptochrome, a protein found in the retinas of birds and other animals, may be the magnetosensor, detecting the direction of magnetic fields via changes to the spin states of some of its electrons.

The hypothesis generated a handful of predictions that Ritz went on to test in collaboration with the biologists who first described magnetoreception in robins, Roswitha and Wolfgang Wiltschko. In a study published in 2004, for example, the team exposed robins to magnetic fields oscillating at frequencies and angles that the model predicted would disrupt the radical pair's sensitivity to the Earth's magnetic field—and effectively knocked out the birds' ability to navigate[14].

The idea has taken off since then, with growing theoretical support. And two 2018 studies of the molecular properties and expression patterns of one version of cryptochrome, Cry4, point to the protein as a likely candidate magnetoreceptor in zebra finches[15] and European robins[16] .

The European robin, *Erithacus rubecula*. Every autumn the birds migrate from Sweden to the Mediterranean, using magneto-reception to navigate. This extraordinary sense involves a chemical called cryptochrome, which is found in many birds and insects. It even exists in maggots.

More work is needed to determine whether or not avian magnetoreception really works this way, and to reveal if entanglement between the electrons of the radical pair is important. Scientists also don't fully understand how cryptochrome could communicate magnetic field information to the brain, says Ritz. Meanwhile, his group is focused on mutagenesis experiments, which could help unravel cryptochrome's magnetosensitivity.

Magnetoreception isn't the only puzzle in animal sensory biology that's generated interest among quantum physicists; another scientifically mysterious sense that researchers hope to help crack is olfaction. The traditional theory—that odorant molecules fit into protein receptors on olfactory neurons to trigger smells—faces the challenge that some molecules with almost identical shapes have completely different odors, while others with different stereochemistry smell alike.

Al-Khalili and McFadden devote a chapter to what they admit is a controversial quantum theory of olfaction. The vast majority of smell scientists consider that our olfactory receptors detect aspects of the molecular shape of an odour – its size, functional group and so on. The problem is that no one has been able to show how this works, nor are we even sure exactly what is detected: is it the smell itself, or smell plus molecular chaperone?

In contrast to this dominant view, there have been suggestions over the years that “quantum tunnelling” in our noses is responsible, and there has been an occasionally acrimonious debate over the validity of these theories. As Al-Khalili and McFadden acknowledge, resolving this issue will involve studying the crystal structure of the receptors (this is very difficult), but they emphasise that the only theoretical explanation for our sense of smell is the quantum one.

Biophysicist Luca Turin proposed that olfactory receptors might be sensitive not just to shape, but to the frequencies of vibrating bonds in odorant molecules[17]. He argued that when an odorant binds to a receptor, if its bonds are vibrating at a certain frequency they can facilitate the quantum tunneling of electrons within that receptor. This transfer of electrons, according to his model, triggers a signaling cascade in the olfactory neuron that ultimately sends an impulse to the brain. The findings are mixed. In 2013, Turin’s group reported that humans can distinguish between odorants containing different isotopes [18]. Two years later, other researchers failed to reproduce the results and called the theory “implausible [19]. But the idea didn’t go out of fashion. In 2016, another team reported that honey bees can differentiate odors with different isotopes[20] , while a recent theoretical study presents a suite of new predictions to help test the model’s validity[21].

Concerning DNA, the theoretical work is also driving interest in quantum biological explanations with far less experimental support. For example, some researchers have speculated that the coherence effects posited to play a role in photosynthesis could also contribute to such widespread biological phenomena as vision and cellular respiration. Others have suggested that proton tunneling could promote spontaneous mutations in DNA, although theoretical work by Al-Khalili and colleagues suggest this isn’t terribly likely, at least for the adenine-thymine base pairs they modeled [22].

One of the most influential people to link quantum physics and biology was Erwin Schrödinger himself, whose book *What is Life?*(1944)[23] inspired, among others, DNA pioneers James Watson and Francis Crick. Al-Khalili and McFadden discuss Schrödinger’s ideas on mutation in some detail, but do not get to their origin.

Quantum Cooperation of Insects

A good part of the communication between the members of a species serves to coordinate their behavior in the interest of common survival. It is generally believed that this communication is governed by the laws of classical physics. Examples would be sound, vibration and direct touch, molecular signalling in the form of smell, and the wide field of behavioral expression, which is physically a method of modulating or emitting patterns of electromagnetic radiation. However, in the newly emerging branch of physics called quantum information [24] it has become clear that many tasks requiring coordination between the actors can be achieved significantly better if the actors' decisions are quantum entangled. The basis for this is Bell's theorem, which proves that observational results obtained at two widely separated but quantum entangled sites can exhibit correlations whose magnitude surpasses that of any correlations conceivable by classical physical laws [25].

Given the importance of correlated action between living systems it is worth while to investigate how quantum entanglement could be embedded beneficially in the stream of sensing, deciding and acting of individuals. In this paper we do this by means of two examples. We show how much farther two cooperating ants could push a heavy pebble, and how much faster two distant butterflies could find each other. Since the quantum entanglement is vulnerable in a thermal environment, the models incorporate the quantum entanglement in the behavior of the individuals in a way which enables them to solve the cooperative task even if the entanglement breaks down, although with less efficiency.

Quantum Biology and Brain:

The brain's qubits, Fisher proposed, are encoded in the states of phosphate ions inside Posner molecules, clusters of phosphate and calcium found in bone and possibly within certain cells' mitochondria. Recent theoretical work by his team argues that the states of phosphate ions in different Posner molecules could be entangled with one another for hours or even days, and may therefore be able to perform rapid and complex computations[26]. Fisher recently received funding to set up an international collaboration, called QuBrain, to look for these effects experimentally. Many neuroscientists have expressed skepticism that the project will turn up positive results.

In fact, Schrödinger's view was based on biophysicist Max Delbrück's theory, put forward in the so-called Three Man Paper, written with geneticist Nikolay Timofeev-Ressovsky and biophysicist Karl Zimmer in 1935.

Schrödinger argued that if Delbrück's view of mutation was wrong, then "we should have to give up further attempts", meaning we would have to give up on using physics to explain genes. Delbrück's approach was correct only at the most general level, and the discovery of the nature of mutations did not refer to his ideas at all.

Real-world applications encompass technologies from more-efficient solar cells to new classes of biosensors. Last year, one group proposed a design for a "biomimetic nose," based partly on the quantum theory of olfaction, to detect tiny concentrations of odorants[27]. And Hore and others have highlighted the radical-pair mechanism that may underlie magnetoreception for use in devices to sense weak magnetic fields.

Thus Quantum Biology May Help Solve Some of Life's Greatest Mysteries.

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