**HOW QUANTUM IS LIFE? FROM PARTICLES TO GENES**

## 1. To what extent is life quantum?

This is the key question. In physical sciences, it was initially thought that the transition from the quantum world to the classical world would occur from a certain dimensional scale. According to this understanding, elementary particles would be the only entities capable of experiencing quantum oddities. It did not take long to notice that these phenomena occur at larger scales - atoms, simple molecules, and subsequently even enormous molecular arrangements containing more than four hundred atoms. With continuous technical and methodological advances, it is possible that in the future, much larger multimolecular systems (that is, a large system composed of several molecules) may prove capable of quantum superposition under very specific conditions. But what, then, would be this dimensional limit from which quantum phenomena would no longer be observed? This is an unresolved question. Currently, some conjecture that any structure (physical or biological) might perhaps exhibit quantum effects, if experimental conditions were adequate. Therefore, all types of life - from the smallest bacteria, to immense whales, and even underground fungal conglomerates, spanning almost ten square kilometers - could experience quantum superposition. However, it is important to emphasize that even if this occurs in laboratories, under very controlled conditions - that is, outside environmental reality - such fact would only be true for exceptional situations. We need to know, to what scale, under regular environmental conditions, life is indeed quantum. In other words: Considering living beings in their natural habitats, are there quantum events occurring in them? To what scale?

## 2. Quantum in the biomolecular domain

Currently, some biomolecular phenomena are known to be based on, or under the influence of, quantum physics. Among them, I might highlight: (i) photosynthesis, in which quantum coherence is experimentally observed in exciton transfer in Fenna-Matthews-Olson complexes and other photosynthetic antennas, in addition to the fact that quantum superpositions allow energy to simultaneously explore multiple pathways, optimizing transport; (ii) enzymatic catalysis, in which protons and electrons can traverse energy barriers through tunneling in various enzymatic reactions, in addition to differences in reaction rates with different isotopes, evidencing quantum tunneling; (iii) cellular respiration, in which quantum tunneling of electrons between protein complexes in mitochondria, in the electron transport chain, is observed.

## 3. Additional biological phenomena that seem to evoke the quantum

In addition to these recognized quantum phenomena in biology, there are some others that seem to evoke the quantum. For example, the oscillation of the third base (inosine) of transfer RNAs. Let's see, next. In a simplified manner, genes are responsible for producing messenger RNAs, which will be used for protein production in our body. This last step is called translation. During translation, codons of a messenger RNA interact with anticodons of transfer RNAs (which are carrying amino acids), like in a lock-and-key system. Thus, if there is a perfect fit between a codon and a certain anticodon, the amino acid carried in that transfer RNA will be incorporated into the protein being produced. However, there is a curious fact - despite there being 64 types of codons, there are only 48 types of anticodons. It is as if there were 64 specific types of locks, but only 48 types of keys! The amazing thing is that there are keys that can open more than one specific type of lock. It is as if some teeth were flexible - this effect being known in Molecular Biology as Wobble pairing. In particular, this impressive fact involves quantum effects.

### 3.1 Wobble pairing (G:T type) involves quantum tunneling

Through nuclear magnetic resonance (NMR) spectroscopy, in an experiment using Hydrogen and Deuterium (a heavier isotope of Hydrogen) in transfer RNAs, researchers obtained data that clearly suggest the existence of proton tunneling in Wobble pairing involving Guanine (G) and Thymine (T) bases. Tunneling is the passage of Hydrogen (or Deuterium) through a high energy barrier - something that is impossible in classical physics. Thus, in tunneling, instead of Hydrogen (or Deuterium) "climbing a hill" (high energy barrier), it "crosses the column underneath" - something that is only possible in quantum mechanics. In other words, researchers created two versions of the same key, which carried a flexible tooth. In one version, the flexible tooth possessed Hydrogen, and in the second version the flexible tooth possessed Deuterium (whose tunneling is more difficult, theoretically). And, as predicted by theory, NMR spectroscopy verified that the key containing Deuterium was less flexible!

### 3.2 Wobble pairings (I:A,U,C types) may involve different quantum phenomena

Inosine is an atypical nucleotide because it is capable of pairing with three different nitrogenous bases (A - Adenine; U - Uracil and C - Cytosine), whereas other nucleotides can adequately pair with only one specific nitrogenous base. Curiously, this possibility of pairing with three different bases emerges from the transition of inosine into different tautomers (that is, different structural forms of the same molecule) that interconvert through the migration of a proton. Thus, inosine tautomerization results in structural variants, each capable of pairing with one of the three bases (A, U, C). In particular, considering experimental data from G:T Wobble pairing, it is possible that inosine tautomerization involves proton tunneling - a quantum event. Alternatively, inosine's ability to pair with three different bases (A, U, C) could be evidence that it (inosine) perhaps exists in multiple simultaneous conformational states, that is, a quantum superposition of tautomeric states! Thus, during codon recognition by the anticodon, decoherence would occur, that is, wave collapse, causing inosine to adopt the most adequate conformational state. To test these hypotheses involving quantum effects in inosine wobble pairing, the following experiments could be conducted (i) NMR studies with isotopic substitution (H/D) in tRNAs containing inosine, (ii) kinetic experiments measuring kinetic isotope effects and (iii) high-resolution structural analyses during dynamic pairing.

## 4. The transition from the quantum world to the classical in Biology

So far, we notice something interesting: quantum mechanics is acting in the biology of living beings, in their environments! However, in all these cases, the phenomena involve electrons, protons, some of which are constituents of biomolecules' structures (and not just free particles). Therefore, quantum events occur in biological systems, with real implications - such as the successful production of sugar and oxygen via photosynthesis. Intriguingly, it can be noted that all these events are located in the "subcellular domain". That is, these are biochemical events, involving biomolecules, but not the entire cell - which is the basic functional unit of life! Thus, quantum phenomena (proton tunneling, for example) are associated with components of biomolecules, which, in turn, also experience such events. However, the cell, as a whole, does not experience quantum phenomena. That is, quantum events are not observed at the cellular level or above. Therefore, just as in the physical realm the transition from quantum to classical seems to be scale-dependent, this also applies to the biological domain. However, in biology, the boundary between one and the other seems to be the functional integration of diverse biomolecules within the cell (that is, metabolism) - an event that would cause, for example, decoherence (that is, wave collapse). The end of observation of quantum phenomena from this level makes sense, because during this integration, various interactions occur between different biomolecules, resulting in decoherence. Thus, from this subcellular level on, all phenomena are classical.

## 5. Quantum events in an entire organism?

In principle, assays to test quantum events at higher levels - cells, tissues or entire living organisms - would be unfeasible. This is because, typically, such experiments involve very low temperatures or vacuum - physical conditions not supported by living beings. However, there is a unique situation in which this could be realized - using organisms capable of entering anhydrobiosis. Anhydrobiosis is a state of suspended animation, which some creatures are capable of entering when exposed to extreme drought. That is, instead of dying from dehydration (like all other organisms), anhydrobionts enter a state in which life stops - literally. That is, metabolism is interrupted; however, reversibly, until the organism is rehydrated again. In particular: when in anhydrobiosis, such organisms are capable of tolerating various types of physical-chemical stresses, such as temperatures close to absolute zero, vacuum, pressure, radiation, among others. Curiously, in 2021, researchers adopted this peculiar condition (anhydrobiosis) and claimed to have detected quantum entanglement between a small invertebrate animal (a tardigrade in anhydrobiosis) and a qubit. There were criticisms, by physicists, questioning whether, in fact, the obtained data evidence the quantum phenomenon. In particular, it is central to highlight that, in the biological scope, the organism was in suspended animation, that is, it did not present metabolism - which is the biological integrating factor responsible for decoherence, for example. Thus, in a way, this experiment, if validated by other groups, would actually contribute to the understanding that, only in the absence of biological integration (or metabolism), is it possible to observe quantum phenomena.

## 6. Does genetics experience quantum events?

Simplifiedly, we could separate Genetics into at least six different levels, which emerged throughout the development of this science. The first is Classical Genetics (1866), focused on the study of heredity factors. The second is Biochemical Genetics (1869), which identified a molecular complex responsible for heredity (nuclein). The third is Cytogenetics, dedicated to the study of chromosomes (1902). The fourth is Molecular Genetics, in which genetic material was defined in its molecular and structural natures (1944). The fifth is Atomic Genetics, in which it was noted that the addition of small chemical groups (that is, a small set of atoms) to DNA and RNA promoted functional differences in them (1950). In particular, in 1963, in his theoretical works, Swedish physicist Per-Olov Lowdin presented the idea that protons could undergo quantum tunneling in hydrogen bonds of DNA bases. Thus emerged the sixth level - Quantum Genetics. This historical trajectory presents a recurring pattern - at each level analyzed (from Mendelian factors to the DNA molecule with added chemical groups), we find elements capable of influencing heredity and physical characteristics determined by genes. Thus, it is very likely that quantum differences exist between messenger RNAs originating from the same gene. These quantum RNA variants - here called QuRNAs - could be identified in the near future, in the context of Quantum Genetics. In this way, the search for variations, no longer molecular or atomic, but of quantum aspects in DNA and RNA, leading to notable biological effects, including alterations in gene expression (for example, higher or lower translation and/or stability rates), could revolutionize our understanding of heredity and, consequently, of all life on Earth.

## 7. Conclusions

Undeniably, biology experiences quantum events. However, considering living beings in their natural states alone (not under ultra-controlled laboratory conditions), all these events are limited to biomolecules, including DNA (genes). Since genetic material (DNA and RNA) experiences quantum phenomena at the molecular level, various physical and behavioral characteristics determined by genes may reflect the influence of underlying quantum processes that have undergone decoherence. Thus, for some of us, our brown eyes may simply be the result of the decoherence of quantum possibilities at the DNA molecular level.