Life on the Edge – The Coming of Age of Quantum Biology

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"Quantum mechanics" and "quantum physics" mean the same thing, although the term *mechanics* emphasizes doing calculations.

4 characteristics of quantum physics

1. **Wave-particle duality**

   ⇨ the defining feature of quantum mechanics

   Describes the behaviour of discrete particles as waves which are spread out rather than particulate, and flowing through space with peaks and troughs – and vice versa.

   Particles can behave like waves spread out across space, and waves can sometimes act like individual localised particles.

   Quantum entities (particles, atoms, molecules) display coherent wave-like behaviour – which means they can interfere with themselves (constructive and destructive interference occur when waves overlap). Quantum interference can take place even when only a single particle is involved (cf two-slit experiment).

2. **Quantum tunnelling**

Discovered in 1926 by the German physicist Friedrich Hund.

Process that allows particles to pass through barriers seen as impenetrable by classical physics – that is, physically impassable regions of space (without sufficient energy) which may consist of a narrow insulating material separating two sides of electric conductors, empty space (such as the gap between two enzymes in a respiratory chain), or a repulsive energy barrier (e.g. limiting the rate of chemical reactions) – because of a probability that the particle would flow through the barrier as a wave (without involving thermal hopping, whereby molecular motion increases with heat).

The lighter the particle, the easier it is for it to tunnel over greater distances (which is why the tunnelling of electrons was found to be the most common). For a body made up of very many particles to tunnel, it has to maintain the wave aspects of all its constituents marching in step, with peaks and troughs of waves coinciding – referred to as the system being coherent, or "in tune". This is why big objects, like footballs, cannot be made to quantum tunnel easily; they are made of trillions of atoms that cannot behave in a coordinated coherent wave-like fashion.

Decoherence describes the process by which molecular noise (random molecular motion and thermal vibrations) disrupts the alignment of quantum mechanical systems, by getting the many quantum waves very rapidly out of step with each other, thereby washing away any coherent behaviour and thus cancelling out the peculiar quantum effects in large inanimate objects.

Quantum coherence is normally expected to be very short-lived unless the quantum system can be isolated from its surroundings (fewer jostling particles) and/or cooled to a very low temperature (much less jostling) to preserve the coherence, and/or provided with the right dose of molecular noise to re-synch the vibrations.

Physicists come up with all sorts of stratagems to shield the quantum world inside their computers from the coherence-destroying outside environment.

Used to explain the concept of radioactive decay; when certain atomic nuclei (such as those of uranium) occasionally spit out a particle. **How?**

Allows pairs of positively charged hydrogen nuclei in the interior of the sun to fuse together (despite the short-range electrical repulsion) in the first step of converting hydrogen to helium, thereby releasing the sun's vast energy.

3. **Quantum superposition**
   Phenomenon whereby particles can do several things at once. A particle can be in a superposition of two or more different states at once – e.g. an electron could be spinning both ways at once (i.e. it could be in a superposition of 'spin up' and 'spin down' states).
   Explains the binding of a proton and neutron in the deuteron (the nucleus of an atom of deuterium), as these two particles exist in two states simultaneously (related to their spin; the "tensor interaction" forces the pair to be in a quantum superposition of two angular momentum states called S-wave and D-wave).

4. **Quantum entanglement (also called nonlocality)**
   The term 'entanglement' to describe this phenomenon was coined by Schrödinger, who was troubled by it – as was Einstein, who referred to it as "spooky action at a distance".
   Feature that allows particles that were once together to remain in instant connection with each other, despite being separated by large distances. In effect, prodding one particle would prompt its distant partner to jump instantaneously.
   Two distant yet entangled particles are said to be non-locally connected, insofar as their quantum state can remain correlated irrespective of the distance between them; measuring just one of an entangled pair immediately collapses the superposition of the other (forcing it to adopt the complementary state), irrespective of how far away it is.

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Some considerations about electrons

An electron can only take a 'spin up' and/or 'spin down' state (its spin can only take two possible values – it is quantized, just as energy is quantized at the quantum level).

Indeed it can, when not being watched, spin in both directions at the same time (in which case it is in a superposition of 'spin up' and 'spin down' states).

An electron needs to make two full rotations to be back to its original state.

Pauli Exclusion Principle

One of its consequences is that if two electrons are paired up in an atom or molecule and have the same energy, then they have to have opposite spin. We can then think of their spins as cancelling out, and we refer to them as being in a spin ***singlet state*** – which is the normal state of pairs of electrons in atoms and most molecules. When not paired together at the same energy level, two electrons can spin in the same direction, and this is called a spin ***triplet state***.

If an electron from a singlet pair sitting in the same atom jumps across into a neighbouring atom, its spin has the possibility of flipping over, creating a triplet state. Despite now being in different atoms, the pair can still maintain their entangled state in which they remain quantum coupled together. But its spin might or might not have flipped over; the pair will exist in a superposition of being in a singlet and a triplet state simultaneously: spinning in the same direction and in opposite directions at the same time.

Free radicals

When the bond between two atoms is broken (these atoms would then be called free radicals), the pair of previously shared electrons remain entangled, with the possibility that the spin of one of them flips over; the entangled electrons (now on different atoms) find themselves in a superposition of both singlet and triplet states.

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Natural expressions of quantum biology

- ***Enzymatic activity***: the distances required for electron or proton particles to jump from one atom/molecule to another in the substrates are too vast and require too much energy to be explained by classical chemistry; they are only made possible by quantum tunnelling (e.g. gap between enzymes in a respiratory chain, or collagenase which breaks the peptide bonds of collagen fibres), which itself is optimised by vibrations of the enzymes' protein backbone.

- ***Photosynthesis***: 1) Energy transport: a photon gets absorbed by an outermost electron of a magnesium atom (part of a chlorophyll molecule from a chromophore sitting on the membrane of a thylakoid inside a chloroplast), thereby generating an exciton, which transfers its energy to neighbouring magnesium atoms' outermost electrons all the way to the reaction centre (where the exciton energy is transformed into a stable chemical form) in close to 100% of cases despite the low probability (considering its lifespan and a classical physics 'random walk') – using a *quantum walk* strategy of route optimisation (i.e. quantum search strategy consisting of following multiple routes at the same time).
  2) Energy transfer: the process occurring inside the reaction centre functions as a quantum heat engine; a *special pair* of chlorophyll molecules with slightly different vibrations exploit quantum interference to inhibit wasteful energy routes, thus pushing the Carnot limit on energy transfer efficiency further.

- ***Olfaction***: odour molecules come in contact with counterpart olfactory receptors at the surface of olfaction cells which have the corresponding chiral shape; if the odour molecule has a bond which vibrates at the right frequency, an electron from the receptor quantum tunnels from donor to acceptor sites (via inelastic electron tunnelling, which requires the bond to vibrate at a frequency equal to the excess energy given by the electron), which gets a G protein to the cell membrane so as to open a channel that allows ions to flow in the cell, triggering an action potential alongside the receptor neuron.

- ***Magnetoreception***: the cryptochrome protein wrapped around the FAD eye pigment molecule absorbs a photon from blue light, thereby forming a pair of free radicals which generates a pair of entangled electrons with the potential to flip their spin upon separation; this leads to a superposition of singlet and triplet states, which is sensitive to magnetism.

- ***Genetic duplication and transcription***: reading the hydrogen bonds linking the nucleic acid bases of DNA occurs at too small a scale for classical physics to apply, as the error rate is too low, pointing at the involvement of quantum physics; it is possible (still debated) that quantum tunnelling provides a way for protons to move across hydrogen bonds to generate the tautomeric, mutagenic, forms of nucleotides.

- ***Neural information processing***: the voltage-gated ion channels across neuronal membranes, responsible for mediating the action potentials (nerve signals), maintain quantum coherence in the passing ions, which enables high transport rates and selectivity – the allowed ions pass as a coherent wave (with constructive interference) by transferring some of their high energy to the surrounding protein, which reduces their kinetic energy and therefore risk of decoherence.

- ***Consciousness***: it is speculated that the brain's EM field may be able to influence nerve firing by affecting the (quantum coherent) voltage-gated ion channels across neuronal membranes – thereby solving the binding problem of getting different nerve impulses to trigger synchronously so as to give way to complex thoughts.

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Practical applications derived from quantum biology

- Synthesis of aromas by techno-scientific methods (instead of the current process of trial and error) – olfaction is based on molecular shapes and the frequency of vibrations of its atomic bonds (see *Olfaction* above), coupled with a mapping system of olfaction receptors and neurones.

- Optimisation of heat engines – the general Carnot limit relative to energy transfer efficiency does not apply to quantum heat engines, for example in the case of photosynthesis – which involves quantic interference (see *Photosynthesis* above).

- Development of self-maintaining structures, such as building walls, through the engineering of a form of synthetic life (that would rely for instance on photosynthesis, cellular respiration, replenishment of the building blocks needed to sustain its structure, etc.) which could detect anomalies and correct them on its own.

- Quantum computers – although their underlying quantum principles are more generic (less specific to biology)