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BOOK REVIEW

QUANTUM ASPECTS OF LIFE EDITED BY DEREK ABBOTT, PAUL C. W. DAVIES AND ARUN K. PATI, WORLD SCIENTIFIC, SINGAPORE (2008)

TOM KIBBLE

Blackett Laboratory, Imperial College London, UK
t.kibble@imperial.ac.uk

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This is a collection of articles on the theme of quantum theory and life, mostly by participants in an astrobiology symposium convened by NASA in 2003. As remarked by Roger Penrose in his preface, this theme was first given prominence in the seminal work "What is Life?" by Erwin Schrödinger, based on public lectures he gave in Dublin in 1943. He argued in particular that the discreteness of genetic information might suggest an underlying quantum mechanical mechanism. Of course, he got many things wrong; he knew nothing of the DNA code. But his book inspired many of those who later worked it out; it effectively kick-started the science of biophysics.

The articles in the present volume cover an extraordinarily varied range. If there is a central theme it can be summarized in two questions: do biologists need to learn quantum theory? Or can they achieve a perfectly adequate understanding of the fundamental mechanisms of life on the basis of classical physics and chemistry? Of course there *are* obvious connections: quantum theory is the foundation of chemistry, as chemistry is of molecular biology. A detailed understanding of the functioning of the processes of life, for example in photosynthesis, requires quantum chemistry. But the real question is whether any of these processes involve in an essential way the more characteristic and esoteric aspects of quantum theory, such as entanglement or the long-range coherence seen in superfluids and superconductors. Reproduction is primarily about replication of genetic information rather than of material objects. The question is, is genetic information processed in an essentially quantum way?

A very particular question is whether quantum theory is needed to explain the *origin* of life: how did the first self-replicator arise? The fundamental difficulty we face in trying to understand how life began is that the simplest self-replicators we know, or even can conceive, are already enormously complex and despite the huge length of time available their assembly by random chemical processes seems overwhelmingly improbable. This is the primary problem addressed by several authors. Paul Davies puts forward the radical idea that the first replicator did not use complex chemistry but rather quantum effects. Quantum mechanics does appear to offer a short-cut in that in principle using quantum coherence one can search through the space of possibilities far more efficiently. The obvious counter-argument is that in the warm, wet environment where life is often thought to have started, decoherence would be rapid. But perhaps the idea could work if life evolved in very special environments or by very special mechanisms.

Seth Lloyd focusses on two features of quantum mechanics that together, he argues, *guarantee* the origin of complexity: it is inherently *digital* and inherently *probabilistic*. The universe is digital; the number of available states on any given scale is finite, and its evolution can be seen as a digital computation. Moreover the probabilistic nature of quantum mechanics injects randomness into the system. The universe apparently began as a very simple system, but it can be regarded as a universal digital computer, and algorithmic information theory shows that such a computer can and will generate huge complexity from very simple input.

A more specific and detailed proposal about how life evolved is presented by Jim Al-Khalili and Johnjoe McFadden. The conventional view is that life started in a "primordial soup" with energy inputs from wind, rain and lightning. Experiments have shown that in a reducing atmosphere rich in methane such stimulation does generate some of the basic ingredients of life — amino acids, sugars and so on. However, there is a big gap between these and molecules such as proteins and nucleic acids, whose formation is hindered by the presence of water and by starting with a racemic mixture of left- and right-handed molecules. Moreover it is no longer believed that the early atmosphere was so reducing. The simplest self-replicating organism we know of has a genome size of half a million base pairs, so how can one bridge the gap? It is not as speculative as it sounds to suppose that quantum mechanics is key; we already know that quantum tunnelling plays a vital role in the conformational restructuring of nucleotide bases responsible for some mutations, and in enzyme catalysis.

A key idea is that of a "dynamical combinatorial library". Imagine a droplet of fluid containing some RNA or amino acid polymers. Even if they are large enough to be self-replicators, they would need to be in precisely the right conformation. The system has to search through the library of possible conformations to find one of the very few that self-replicates. The problem is that relying on chemical changes — the breaking and reforming of covalent bonds — this search is a very slow process. But suppose the changes occur by quantum tunnelling, as in the tautomerization that connects *enol* and *keto* forms of nucleotide bases. That is a much faster process, and moreover quantum superposition allows a simultaneous search of many different possibilities. Of course, this raises the question, how can we avoid decoherence? There are at least two possible answers. Most obviously, the system may be isolated from any environmental interaction, perhaps in a tiny pore in the rock. The second is almost the reverse: paradoxically, a strong but specific interaction with the environment can amount to a repeated measurement, and so induce a "quantum Zeno effect", enabling coherent superpositions to persist.

The idea that quantum dynamics is involved in photosynthesis is discussed by Alexandra Olaya Castro, Francesca Favioli Olsen, Chiu Fan Lee and Neil Johnson. The central step in photosynthesis is remarkably fast and efficient: excitation transfer to a molecular complex serving as a reaction centre occurs in a few hundred picoseconds, and most absorbed photons give rise to a charge separation event. There is some evidence, albeit controversial, that quantum coherence is involved. Castro *et al.* present a theoretical model of a coherent photosynthetic unit, motivated by the photosynthetic apparatus of purple bacteria, involving coherent excitation transfer between donors and acceptors in a circular arrangement. They show that the model could work at low temperature and discuss the prospects for experimental tests.

The key process of decoherence in biomolecules is discussed by Jacques Bothma, Joel Gilmore and Ross McKenzie. They present a number of different "minimal models" describing essential aspects of the interactions between complex systems, with the aim of deciding which environmental interactions contribute most to decoherence in various biomolecules, and thereby testing ideas about the operation of enzymes and possibly devising more efficient systems of artificial photosynthesis. They show that interaction with the environment does make quantum effects like interference and tunnelling less significant. In biological chromophores, increasing the strength of the interaction increases the decoherence rate. In hydrogen transfer reactions in enzymes, environmental interaction depresses the temperature at which quantum effects impinge.

The role of quantum effects in the molecular machines (polymerases) that read and write DNA is discussed by Anita Goel. The aim is to understand the various "knobs" that control the "tuning" or "switching" behaviors of the motor. A key input is provided by the constraints derived by Wigner in 1957 on the running time and precision of a microscopic clock or other information-processing device. These are used to provide estimates of the efficiency and information-processing power of a motor. Goel argues that the information content of a DNA-motor system is much larger than hitherto assumed, of order 10^5. Moreover, the decoherence time can be very long, of order minutes to hours, leaving the way open for significant quantum effects.

Another area of hot debate about the relevance of quantum effects is to memory and consciousness, addressed here by Andreas Mershin and Dimitri Nanopoulos. Some have believed that consciousness must be associated with quantum theory essentially because both are ill understood! This argument they characterize as akin to the "god of the gaps" argument for the existence of a deity. Nevertheless, there *may* be a connection. If so, there must be some kind of amplification mechanism that renders quantum effects at the atomic or molecular scale relevant to the cellular-scale processes underlying consciousness. The authors suggest three kinds of experiments at different scales that may be used to test the "quantum consciousness idea". In all three cases, some relevant experiments have already been done. The idea is least likely to work, Mershin and Nanopoulos argue, on the tissue-to-cell scale, where environmental decoherence is hard to avoid. Experiments on the cell-to-protein scale are important because they can in principle rule out many of the variants of the quantum consciousness idea. In particular, the authors discuss the hypothesis that the internal cavities of microtubules function as quantum-electrodynamic cavities, and that memory is affected by perturbations in the microtubular cytoskeleton. They describe experiments on *Drosophila* that appear to lend some support to this idea.

On the third scale, protein-to-atom, quantum effects are believed to be important in some processes, such as photosynthesis and the action of enzymes. But the real question is whether there is any amplification mechanism that makes them relevant on larger scales too. As usual, the primary issue is whether one can avoid decoherence. The authors point out that although tubulin molecules comprise some 17,000 atoms, the mesoscopically relevant dipole moment state depends on only a few electrons, so tubulin could indeed maintain decoherence for times of the order of microseconds. They also suggest ways of testing whether biological matter can carry quantum entangled states.

The idea of quantum metabolism is described by Lloyd Demetrius. There are empirical scaling relations governing the basic metabolic rate of an organism. The hypothesis here is that these relations are grounded in the discreteness of quantum energy levels. Metabolic activity is not driven primarily by temperature differences but by ion-gradients. It is localized in energy-transducing membranes, involving the coupling of an energy-donating oxidation-reduction reaction to an energy-accepting ATP phosphorylation. Here the fundamental unit of energy, analogous to the thermal energy kT in a vibrating solid, is related to the metabolic cycle time. Using a multi-scale hypothesis, this model can be used to predict scaling relations for different types of organism.

As is well known, symmetries have played a big role in particle physics, bringing order to the rich particle zoo. The genetic code is hugely complex but shows similar regularities. So it is not surprising that particle physicists have sought to extend their models to analysis of the code. Jim Bashford and Peter Jarvis discuss the evolution of the code and suggest a possible role for quantum processes at important stages of codon reading and translation. Remarkably, they also suggest there is evidence in the systematics of the genetic code for an underlying supersymmetry.

A different approach to this problem is taken by Apoorva Patel, treating life as an exercise in information theory. The essence of life, he suggests, is that hardware is recycled while software is refined. The aim is to understand the physical and evolutionary reasons for the genetic languages and their realization — currently, the four-nucleotide language of DNA and RNA and the protein-coding language based on twenty amino acids. He argues that the languages have evolved to optimize information-processing efficiency. Optimization has progressed faster and farther at the lower levels (cells) than the higher (organisms, communities). Patel discusses the information-processing requirements for the two languages and shows in particular how well suited amino acids are for encoding proteins and how close the four-base DNA language is to being optimal in information-theoretic terms. He suggests that in the course of evolution the current language may have evolved by a process of duplication from an earlier one with a doublet code for labelling ten amino acids. Striking evidence for this idea can be found in the current code. He also suggests there are good information-theoretic reasons for thinking that quantum processes are involved in the reading and writing of genetic information.

Several contributors do not directly address the central question of quantum mechanics and life, but deal rather with the rapidly expanding field of *artificial* quantum life. The "no-cloning theorem" forbids the copying of quantum states. But as Arun Pati and Samuel Bronstein point out, it does not directly forbid self-replication of a quantum system. They ask whether a universal quantum constructor exists, analogous to the classical universal constructor whose existence was proved by von Neumann. They prove, using a very simple, direct argument, that no deterministic universal quantum constructor operating with finite resources can exist. However, a constructor could exist that would allow probabilistic self-replication with some probability of error.

A "semi-quantum" version of John Conway's "Game of Life" is presented by Adrian Flitney and Derek Abbott. A fully quantum version on an infinite lattice would be impossible but in a semi-quantum version, of which several variants are discussed, cells are represented by classical sine-wave oscillators, allowing for superposition and interference effects.

Quantum games are discussed by Azhar Iqbal and Taksu Cheon, in particular the concept of an "evolutionarily stable strategy". In the context of living organisms, a strategy is the analog of a genotype; an evolutionarily stable strategy is one that, if adopted by the whole population, cannot be successfully invaded by another genotype that appears in a small fraction of the population. In a long and detailed analysis, Iqbal and Cheon show that quantization of games can in certain circumstances lead to the appearance of new stable equilibria. This may be of relevance to biology.

Yet another perspective is provided by Edward Piotrowski and Jan Sładkowski, discussing the esoteric concept of quantum transmemetic intelligence. A "qumeme" is a quantum version of Richard Dawkins's "meme", as a qubit is of a bit. The concept may have application in the functioning of the genetic code. The authors discuss such intriguing ideas as a quantum model of free will and counter-factual measurements as a model of intuition.

Among the most interesting parts of the book are the transcripts of two debates. The first, from 2003, was on "Dreams versus Reality" in Quantum Computing. The question under discussion was whether it is probable that we can build a *useful* quantum computer within a reasonable number of years. Or is this just a dream? On the side of Reality, arguing that one would indeed be built, were Carl Caves, Daniel Lindar, Howard Brandt and Alex Hamilton. Against them, arguing that twenty years of work by huge numbers of people have only served to make the obstacles clearer, were David Ferry, Julie Gea-Banaloche, Sergey Berzukov and Laszlo Kish. The panel generated a very lively debate, without, however, reaching any definite conclusion.

The second debate, staged in 2004, was on the central theme of this volume: "Quantum Effects in Biology: Trivial or Not?" Arguing for non-triviality were Paul Davies, Stuart Kameroff, Anton Zeilinger and Derek Abbott; for triviality, Jens Eisert, Howard Wiseman, Sergey Berzukov and Hans Frauenfelder. The debate is fascinating to read; because of the immediacy of the format the basic arguments emerge in some ways more clearly than in the earlier chapters, where they sometimes get lost in the detail. Both sides presented strong cases. Neither won; at the end, the audience was nearly evenly divided.

Perhaps as a counterbalance to the earlier chapters, two of those who participated on the side of triviality, Howard Wiseman and Jens Eisert, were later asked to contribute a chapter of their own, setting out "A Skeptical Physicist's Point of View". They go through all the various arguments advanced for non-trivial effects and offer often cogent counter-arguments.

On the other side of the argument, the book closes with a fascinating and powerful contribution from one of the main proponents of a quantum basis of life, Stuart Hameroff. Here he expands on one particular idea, that the key aspect of life can be found in cooperative quantum processes in lattices of π-electron resonance clouds in biomolecules. These clouds are largely isolated from cell water and ions, reducing the rate of decoherence. In repetitive structures like DNA the close lattice spacing is conducive to electron tunnelling and non-local quantum processes. This, Hameroff argues, is the real basis of life.

Understanding the fundamental nature and origin of life is perhaps the most challenging and important of scientific quests. One of the key arguments is whether specific quantum effects are involved. There are cogent arguments on both sides of the debate. To anyone wishing to understand and evaluate them, this book offers a clear and wide-ranging introduction.