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ESSAY REVIEW

Quantum aspects of life

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A review of **Quantum Aspects of Life**, edited by D. Abbott, P.C.W. Davies and A.K. Pati, London, Imperial College Press, 2008, xxvi + 442 pp., £35.00 (paperback), ISBN 978 1 84816 267 9. Scope: edited volume. Level: undergraduate and postgraduate scientists and engineers.

In our everyday macroscopic world, quantum mechanics seems not to matter and nobody thinks about it. Physical quantities like position, momentum, energy and time all seem well defined, albeit subject to the experimental errors in their measurement. Pedestrians do not become entangled or interfere with each other – at least not quantally – and although prisoners may occasionally escape from their cells, it is never by quantum tunnelling. To all intents and purposes, quantal effects are totally absent. The reason, of course, is that the de Broglie wavelengths of moving macroscopic objects and people are tiny compared to other characteristic lengths like their sizes and separations, so that everything appears sharp edged and well defined.

As one moves to examine matter on progressively smaller scales, however, the picture starts to change. On atomic dimensions and below, one is usually considering objects of very small mass, with small momentum, and correspondingly large de Broglie wavelength, so quantum mechanics dominates. In liquid helium, for example, the wavelengths of individual atoms become larger than the average atomic separation. It then makes little sense to think of individual atoms at all. Rather, there is a ‘soup’ of intermingling waves that can only be discussed collectively. To describe gas-like ensembles like the liquid heliums, or the electron gas in a metal, quantum statistical mechanics is essential and the symmetry of the wavefunction plays a key role: Bose–Einstein statistics for ^{4}He where the atomic wavefunction is symmetric; and Fermi–Dirac statistics for ^{3}He and electrons, or for the neutrons in a neutron star, where it is antisymmetric. At low enough temperatures (where thermal velocities and momenta are small enough) there may be a phase transition to a quantum coherent state like superfluidity or superconductivity. Here, ‘low enough’ can be enormously variable, depending on the system. The lowest known superconducting transitions are in the millikelvin temperature range, but the high-T_c materials can become superconducting above 100 K, and the nucleonic superfluids of a neutron star may exist at 10^4 K. Such phenomena are inexplicable in classical terms, and a quantum mechanical description is absolutely essential.

But what about life? Is quantum mechanics necessary to explain the function of living systems? Most of the processes that constitute life – e.g. the chemistry of large molecules and the operation of subcellular motors – occur on scales that lie uneasily close to the fuzzy dividing line between the classical and quantum-dominated worlds. So there are no easy answers. Of course, there is a trivial sense in which quantum mechanics is important for life as, indeed, for everything else. The entire Universe (including living matter) is subject to quantum mechanical laws; and both the shapes and interactions of the protein molecules are obviously determined by quantum mechanics. But molecular biology developed mostly by consideration of ‘ball-and-stick’ models of molecules, i.e. by modelling life at a level above that at which quantal effects need to be considered explicitly. But the question remains: are there any processes in living systems where nontrivial quantum mechanical effects are important? One is thinking here of the quintessentially quantal phenomena such as tunnelling, coherence, entanglement, superposition and so on. Even though the broad-brush picture of how living systems function, and how they evolved on Earth, is almost universally accepted, there remain many aspects that are still mysterious. So perhaps quantum mechanics plays a central role in one or more of them?

These are profound questions. *Quantum Aspects of Life* tackles them head-on, and does so from many different directions. The book consists of 16 chapters by specialists and two chapters that take the form of debates, together with a Foreword by Sir Roger Penrose and a Preface by the editors which together set the scene and orientate the reader for what follows.

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In part, the work derives from a conference at the NASA Ames Research Center on the same subject. The participants were invited to contribute essays on the theme, and so also were a wider group of sceptical scientists. Thus, the author(s) of each chapter put(s) forward their own particular viewpoint on the question. They come from a very broad range of different backgrounds including theoretical physics, biology, cosmology, astrobiology, mathematics, high energy physics, mechanical engineering, biomedical engineering, evolutionary biology, molecular genetics, biophysics, quantum information science, quantum computing, quantum game theory, many-body theory, and anaesthesiology. Despite this diversity of training and approach, there is a fair amount of repetition because each essay strives to be self-contained. The genetic code, for example, is explained many times at different levels of detail. But each presentation provides a slightly different perspective, and this certainly aids understanding.

The two debates took place at the 3rd and 4th Fluctuations and Noise conferences, in Santa Fe and Gran Canaria, respectively, and are reproduced verbatim. The first one, addressing the question of whether quantum computing is just a dream or could become reality, might seem an unexpected inclusion at first sight. However, it is highly relevant given that some scientists argue in favour of quantum processing in biological systems. Correspondingly, those involved in the quest for man-made quantum computers sometimes appeal to biology in the face of scepticism about their feasibility – despite the lack of firm evidence that such processes really occur in biological systems. The second debate addresses the question 'Quantum effects in biology: trivial or not?' and is thus central to the topic of the book. It exposes the competing arguments in a very readable and interesting way, partly because the scientists involved feel able to be more forthcoming and freely expose their own personal opinions and knowledge and ignorance.

The latter debate ranged widely, and is hard to summarise, but those that spoke against there being non-trivial quantal effects in biology pointed to the lack of direct evidence for them: e.g. no qualitatively new insights have yet emerged that would make a biologist feel the need to go and take a second year course in quantum mechanics. In any case, biological systems are warm and wet and noisy, and just not the kind of place where delicate quantum coherence effects could be anticipated. The elementary operations of the brain (synaptic transduction between neurons) are understood in great detail as dissipative macroscopic processes, and non-trivial quantal effects do not enter. Those in favour of the existence of non-trivial quantal effects in biology emphasised that we live in a quantum mechanical universe, that life therefore emerged from quantum mechanics, being ultimately molecular, and that it makes little sense to suggest that quantal effects should disappear as soon as life gets going. The conformational dynamics of proteins is mainly governed by quantum mechanical van der Waals forces (because the high-energy Coulomb interactions mostly cancel out), and involves quantum switches and superpositions of conformational states that amount, in effect, to protein qubits: some proteins, e.g. microtubules seem well suited to act as quantum computers, potentially conferring an enormous evolutionary advantage. There is, in fact, evidence for the involvement of microtubules and the cytoskeleton in learning and memory, at a level far below that of neural transduction. The (mysterious) function of anaesthetics was proposed as indirect evidence for e.g. quantum computation in the brain. The anaesthetic molecules are actually inert – even the inert gas xenon will serve the purpose perfectly well. They travel to hydrophobic pockets that govern the dynamics of certain proteins in the brain, interfering with the normal van der Waals forces, inhibiting protein quantum switching, and erasing consciousness while other brain activities continue. So the suggestion here is that the brain, and particularly consciousness, may involve much more than just synaptic transduction. At the end of the debate, the numbers voting for and against the motion were roughly equal, with a small majority for there *not* being any non-trivial quantal effects in biology. There was, however, a large majority in favour of undertaking some experiments to pursue the ideas further.

It seems very clear that life is already understandable in remarkable detail at the point where physics, chemistry and biology all meet. And yet ... there still remain some enduring mysteries. For example, how did life get started, i.e. how did the first replicator arise (either here or elsewhere in the Universe)? Where do consciousness and self-awareness come from? Are they just examples of emergent phenomena in a sufficiently complex system, or is there more to them than that? As Sir Roger Penrose points out in his Foreword, few biologists believe that any fundamental new principle is needed here: we should expect to be able to account for life and consciousness in all their complexity from a subset of the twentieth-century physics we know all about already, and especially the laws of mechanics and electromagnetism. The point at issue is of course whether or not quantum mechanics is also an essential ingredient. One attractive aspect of the hypothesis is that it offers an immediate explanation of the 'binding problem', at least on an intuitive level. This problem arises from the fact that an object, e.g. a barking dog, is consciously perceived as a single entity despite involving the widely separated areas of the brain where vision, sound, smell, movement, etc. are processed, which have relatively little in the way of direct neural connection. The inherent nonlocality of quantum processes is obviously attractive in this context. But non-quantum solutions to the binding problem can also be imagined, for example based on classical synchronisation phenomena where the brainwaves associated with the different processing centres all come into mutual synchronisation to bind together the different aspects of 'dog' into a single entity. The brainwaves themselves arise from the coupled oscillatory behaviour of the huge number ($\sim 10^{11}$) of neurons in the brain, each of which has a huge number (~ 7000 on average) of interconnections with other neurons, creating a system of unparalleled complexity in which the occurrence of emergent phenomena would hardly come as a surprise. Of course, in themselves, neither quantum nor classical explanations of brain function can account for conscious awareness of the dog (or of anything else), but one of them could perhaps represent a step towards understanding the corresponding physiological processing mechanisms, thus bringing us a little closer to an understanding of the central problem of consciousness. But for now the mystery remains.

Several of the contributors refer to Schrödinger's pioneering book *What is Life?* which was of course written at a time when much less was known than now about life's molecular basis. In the final chapter Stuart Hameroff suggests, with reasons, that 'It is time to reconsider pioneering suggestions by Erwin Schrödinger, Albert Szent-Györgyi, Alberte and Phillip Pullman, Herbert Fröhlich, Michael Conrad and many others that life's essential feature involves quantum effects in and among geometrically arrayed π electron clouds in non-polar regions of carbon-based chemistry.' Of course, there is room to argue whether or not such effects would be non-trivial, even if the idea is correct, but the statement seems admirable in its succinctness.

Quantum Aspects of Life provides an extraordinarily rich diet of ideas and information, in fact far too rich to take down in a single gulp, at least for most people. The individual chapters vary in accessibility from ones suitable for undergraduates, or even advanced school students, to a few that are really aimed at other specialists – and there is everything in between as well. Most authors have taken the task very seriously and have produced self-contained contributions with extensive references to the original literature. Anybody can read the debates with understanding and enjoyment. Each chapter deserves close reading, followed by an extended period of cogitation. So what is the 'bottom line'? It will be for the individual reader to decide for herself or himself, but they have here a huge mass of authoritative material – as well as stimulation from the more discursive discussions in the debates – on which to base their conclusion. For me personally, the jury is still out, and I eagerly look forward to further developments in this fascinating area.