Chapter 1

A Quantum Origin of Life?

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The origin of life is one of the great unsolved problems of science. In the nineteenth century, many scientists believed that life was some sort of magic matter. The continued use of the term "organic chemistry" is a hangover from that era. The assumption that there is a chemical recipe for life led to the hope that, if only we knew the details, we could mix up the right stuff in a test tube and make life in the lab.

Most research on biogenesis has followed that tradition, by assuming chemistry was a bridge—albeit a long one—from matter to life. Elucidating the chemical pathway has been a tantalizing goal, spurred on by the famous Miller-Urey experiment of 1952, in which amino acids were made by sparking electricity through a mixture of water and common gases [Miller (1953)]. But this concept turned out to be something of a blind alley, and further progress with pre-biotic chemical synthesis has been frustratingly slow.

In 1944, Erwin Schrödinger published his famous lectures under the title *What is Life?* [Schrödinger (1944)] and ushered in the age of molecular biology. Schödinger argued that the stable transmission of genetic information from generation to generation in discrete bits implied a quantum mechanical process, although he was unaware of the role of or the specifics of genetic encoding. The other founders of quantum mechanics, including Niels Bohr, Werner Heisenberg and Eugene Wigner shared Schrödinger's belief that quantum physics was the key to understanding the phenomenon

Received May 9, 2007

of life. This was a reasonable assumption at the time. Shortly before, quantum mechanics had solved the problem of matter, by explaining atomic and molecular structure, chemical bonds and the nature of solids. It seemed natural that quantum mechanics would soon also solve the riddle of the living state of matter. To a physicist, life seems fundamentally weird, even bizarre, in its properties, and bears almost no resemblance to any other type of physical system. It is tempting to suppose that quantum mechanics possesses enough weirdness to account for it.

These early musings about the place of quantum mechanics in life were soon swept away in the rush. Molecular biology proved so successful that rich pickings could be harvested merely from crude ball-and-stick models of molecules. However, with the maturity of the subject, hints began to surface that non-trivial quantum effects might be of crucial significance in the functioning of certain biosystems. Some of these effects are reviewed in other chapters in this volume. The question I wish to address in this chapter is in what manner quantum mechanics played a role in the origin of life. One point needs clarification. There is a trivial sense in which life is quantum mechanical. Cellular function depends on the shapes of molecules and their chemical affinities, properties that require quantum mechanics to explain. However, what I have in mind are non-trivial quantum effects, for example, the coherent wavelike nature of matter, tunnelling, entanglement, intrinsic spin, Berry phase, environmental post-selection and the watchdog effect.

Obviously at some level quantum mechanics cannot be ignored in the life story, since by general consent, life somehow emerged from the molecular realm, even if the specifics remain mysterious. The molecular road to life is in contrast to the "magic matter" theories of the nineteenth century that were essentially macroscopic in conception. Because the molecular realm is unquestionably quantum mechanical in nature, the issue I am raising is whether classicality emerged before life or whether life emerged before classicality. My central hypothesis is that quantum mechanics enabled life to emerge directly from the atomic world, without complex intermediate chemistry. The orthodox view is that an extended period of increasingly complex "ball-and-stick" chemistry preceded the transition to the first genuinely autonomous living system (which may not have been an individual cell, more likely it was a cellular cooperative). The philosophical position that underpins my hypothesis is that the secret of life lies not with its complexity per se, still less with the stuff of which it is composed, but with its remarkable information processing and replicating abilities.

1.1. Chemistry and Information

Although there is no agreed definition of life, all living organisms are information processors: they store a genetic database and replicate it, with occasional errors, thus providing the basis for natural selection. The direction of information flow is bottom up: the form of the organism and its selective qualities can be traced back to molecular processes. The question then arises of whether, since this information flows from the quantum realm, any vestige of its quantum nature, other than its inherent randomness, is manifested. Biological molecules serve the role of both specialized chemicals and informational molecules, mirroring the underlying dualism of phenotype/genotype. In computer terminology, chemistry is akin to hardware, information to software. A complete understanding of the origin of life demands an explanation for both hardware and software. Most research in biogenesis focuses on the hardware aspect, by seeking a plausible chemical pathway from non-life to life. Though this work has provided important insights into how and where the basic building blocks of life might have formed, it has made little progress in the much bigger problem of how those building blocks were assembled into the specific and immensely elaborate organization associated with even the simplest autonomous organism [Davies (2003)]. But viewing life in terms of information processing transforms the entire conceptual basis of the problem of biogenesis. Reproduction is one of the defining characteristics of life. Traditionally, biologists regarded reproduction as the replication of material structures, whether DNA molecules or entire cells. But to get life started all one needs is to replicate information. In recent years our understanding of the nature of information has undergone something of a revolution with the development of the subjects of quantum computation and quantum information processing. The starting point of this enterprise is the replacement of the classical "bit" by its quantum counterpart, the "qubit". As a quantum system evolves, information is processed; significantly, the processing efficiency is enhanced because quantum superposition and entanglement represent a type of computational parallelism. In some circumstances this enhancement factor can be exponential, implying a vast increase in computational speed and power over classical information processing. Many researchers have spotted the sweeping consequences that would follow from the discovery that living organisms might process information quantum mechanically, either at the bio-molecular level, or the cellular/neuronal level [Penrose (1989); Beck and Eccles (1992); Hameroff (1994); Davies (2004);

Matsuno (1999); Patel (2001); Vedral (2003); Schempp (2003)]. Biological systems are quintessential information processors. The informational molecules are RNA and DNA. Although quantum mechanics is crucial to explain the structure of these molecules, it is normally disregarded when it comes to their information processing role. That is, biological molecules are assumed to store and process classical bits rather than qubits. In an earlier paper [Davies (2004)] I speculated that, at least in some circumstances, that assumption may be wrong. It is then helpful to distinguish between three interesting possibilities:

(1) Quantum mechanics played a key role in the emergence of life, but either ceased completely to be a significant factor when life became established, or was relegated to a sporadic or subsidiary role in its subsequent development. Nevertheless, there may be relics of ancient quantum information processing systems in extant organisms, just as there are biochemical remnants that give clues about ancient biological, or even pre-biological, processes.
(2) Life began classically, but evolved some efficiency-enhancing "quantum tricks." For example, if biological systems were able to process information quantum mechanically, they would gain a distinct advantage in speed and power, so it might be expected that natural selection would discover and amplify such capabilities, if they are possible.
(3) Life started out as a classical complex system, but later evolved towards "the quantum edge," where quantum uncertainty places a bound on the efficiency of bio-molecular processes.

As there is little doubt that some cellular machinery (e.g. photosynthesis—see Chapter 4) does exploit quantum mechanics [Engel *et al.* (2007)], the issue arises of whether quantum enhancement is a product of evolution (as in 2), or a remnant of life's quantum origin (as in 1).

1.2. Q-life

The starting point of my hypothesis is the existence of a quantum replicator, a quantum system that can copy information with few errors [Wigner (1961); Pati (2004)]. The information could be instantiated in the form of qubits, but that is not necessary—the quantum replication of classical bits is sufficient (see below). A quantum replicator need not be an atomic system that clones itself. Indeed, there is a quantum no-cloning theorem

that forbids the replication of wavefunctions [Wooters and Zurek (1982); Pati (2004)]—see also Chapter 11 in this book. Rather, the information content of an atomic system must be copied more or less intact—not necessarily in one step, maybe after a sequence of interactions. This information might well be in binary form, making use of the spin orientation of an electron or atom for example. Quantum mechanics thus provides an automatic discretization of genetic information. Quantum replicators certainly exist in Nature. The simplest case is the stimulated emission of photons. Another is the atom-by-atom growth of a crystal lattice. But these examples are not information-rich; they do not fulfill the additional requirement of high algorithmic complexity demanded by biology, as neither the identical photons not the identical crystal atoms store more than a very few bits of information. So we seek a natural system in which high-fidelity replication of an information-rich assemblage of quantum objects takes place on a short time scale. Henceforth I shall refer to this hypothetical system as Q-life. Leaving aside wild speculations like life in neutron stars [Forward (1980)], a venue for Q-life might plausibly be a condensed matter setting at a low temperature, for example, the crust of an icy rogue planetesimal in interstellar space.

Let me illustrate the basic idea of Q-life with a simple, and almost certainly unsatisfactory, example. Consider an array of atomic spins embedded in a condensed matter system, defined relative to some fiducial direction. The initial template A may be described by a ket vector such as

$$|\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow\rangle \ .$$

This template then comes into interaction with an arbitrary system of spins B, say,

$$|\uparrow\uparrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\rangle \ .$$

As a result of the interaction (which may entail many intermediate steps), the following transition occurs

$$|\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow\rangle\,|\uparrow\uparrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\rangle \longrightarrow$$

$$|\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow\rangle\,|\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow\rangle \ .$$

Symbolically, the overall evolution of the state is $AB \longrightarrow AA$. Because the transition has erased the information contained in state B, the replication process is asymmetric and irreversible, and accompanied by an increase in entropy. The system thus requires an energy source to drive the reaction forward. This could be in the form of an exciton that hops along the array of atoms, flipping the B spins where necessary one-by-one but leaving the A spins unchanged.

The foregoing model is very simplistic. A more realistic form of interaction, and a closer analogue of DNA replication, would be if the template array A first created a complementary array

$$|\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\downarrow> ,$$

which then generated the original array by "base-pairing". An additional simplification is that the model described so far neglects interactions between neighbouring spins. Such interactions produce greater complexity, and so increase the opportunity to encode algorithmically incompressible information.

The replication rate of a spin array will depend on whether the sequence is processed linearly, after the fashion of DNA, or all at once. It will also depend on the availability of the necessary complementary structure. Once the two structures are brought into interaction, each bit flip could occur extremely fast (i.e. in less than a femtosecond). This can be compared to the sluggish rate of only 100 base-pairs per second typical of DNA replication by polymerase enzymes, even when the system is not resource-limited [Goel *et al.* (2003)]. Thus, in an appropriate quantum setting, Q-life could replicate and evolve at least 12 orders of magnitude faster than familiar life! However, in practice an ideal appropriate setting is unlikely to occur in nature. More realistic is a model of replication in which the process is managed by a catalytic structure, in analogy with the replicase enzymes of DNA replication. The job of this conjectured structure would be to bring the required components into interaction, perhaps by creating an "interaction centre" screened from the environment. The replication rate would then be limited by the performance of this "Q-replicase." In particular, the Q-replicase is likely to be subject to the opportunities and limitations of quantum mechanics. In the later category are fundamental limits of choreography set by the uncertainty principle, a topic that I shall defer to the final section.

How, then, did organic life arise? Information can readily be passed from one medium to another. At some stage Q-life could have co-opted large

organic molecules for back-up memory, much as a computer uses a hard-disk. The computer's processor (analogous to Q-life) is much faster than the hard disk drive (analogous to RNA and DNA), but more vulnerable and in need of a continual input of energy. Robust computing systems require something like a hard disk. Eventually the organic molecular system would literally have taken on a life of its own. The loss in processing speed would have been offset against the greater complexity, versatility and stability of organic molecules, enabling organic life to invade many environments off-limits to Q-life (e.g. high temperature).

Note that although the replicator I have used as a simple illustration is fundamentally quantum mechanical in nature, the copying process as described does not replicate any entanglement or phase information; i.e. the process replicates bits rather than qubits. For that reason, decoherence would not be an issue at the replication stage. Left out of the account so far, however, is how the quantum replicator arises in the first place. The nature of the transition from an arbitrary quantum system to a replicating quantum system is far from clear, but the process is likely to be enormously enhanced if it is at least partially coherent. Let me therefore make some general remarks about decoherence in biosystems.

1.3. The Problem of Decoherence

Coherence entails the preservation of delicate phase relationships between different components of the wave function. Interactions between the quantum system and its environment will serve to decohere the wave function: the noise of the environment effectively scrambles the phases. Once decohered, a quantum system behaves in most respects as a classical system [Zurek (1982)]. The decoherence rate depends on the nature and temperature of the environment and the strength with which it couples to the quantum system of interest [Zurek (1982); Caldeira and Leggett (1985); Unruh and Zurek (1989); Hu *et al.* (1992)]. The main burden in the development of quantum computation, for example, is to screen out the decohering environment as efficiently as possible, e.g. by reducing the temperature. If quantum mechanics is to play a role in the origin of life, typical decoherence rates must not be greater than the relevant transition rates. Simple models of decoherence have been much studied over the past twenty years. Typically, for a particle interacting with a heat bath at room temperature, exceedingly short decoherence times result. Translated into the context of,

say, a nucleotide in the environment of a cell at room temperature, decoherence times of femtoseconds are typical, [Caldeira and Leggett (1985); Unruh and Zurek (1989); Hu *et al.* (1992); Tegmark (2000)]. But on a second look, the situation is found to be more subtle. There are two ways in which decoherence could be diminished for long enough to enable biologically important processes to occur. The first is screening: if the system of interest can be quasi-isolated from the decohering environment then decoherence rates can be sharply reduced. According to Matsuno (1999), organisms may exploit thermodynamic gradients by acting as heat engines and thereby drastically reduce the effective temperature of certain molecular complexes. He cites the example of the slow release of energy from ATP molecules at actomyosin complexes, which he claims implies an effective temperature for the actomyosin of a mere 1.6×10^{-3} K. At any rate, the lesson of high-temperature superconductivity reminds us that in complex states of matter, simple "kT reasoning" can be misleading.

The second possibility involves decoherence-free subspaces. In the effort to build a quantum computer, much attention has been given to identifying subspaces of Hilbert space that are unaffected by the coupling of the system to its environment [Nielson and Chuang (2001)]. Paradoxically, when a system couples very strongly to its environment through certain degrees of freedom, it can effectively "freeze" other degrees of freedom by the quantum Zeno effect, enabling coherent superpositions and even entanglement to persist. An explicit example is provided by a double-well one-dimensional potential. A particle placed in the lowest energy state of one well will tunnel back and forth through the intervening barrier, oscillating with a certain frequency. If the particle is placed instead in an excited state of the well, this flip-flop frequency will be different. Thus an initial state consisting of a superposition of lowest energy and excited states will soon evolve into a complicated muddle as the flip-flops get out of phase. However, if the particle is now allowed to interact strongly with an external heat bath, the environment has the effect of forcing the disparate oscillations into synchrony, thereby maintaining a limited form of quantum coherence, not in spite of, but because of, environmental interactions [Davies (2003)]. Furthermore, if the system is placed in an entangled state of left and right well-locations, this entanglement is also preserved by environmental interaction. The model was developed in the context of neutrino oscillations, but has general applicability [Bell *et al.* (2002)]. It does, however, depend on the interaction being "blind" between the two potential wells. It is unclear how realistically this would translate into a biological scenario, or whether

it has any relevance to the extended decoherence times reported recently [Engel *et al.* (2007)].

1.4. Life as the "Solution" of a Quantum Search Algorithm

The hypothesis I am proposing is that the transition from non-life to life was a quantum-mediated process, and that the earliest form of life involved non-trivial quantum mechanical aspects. The power of quantum superpositions is that the system can explore many alternative pathways simultaneously, thereby potentially shortcutting the transition time by a large factor. Because life is a highly unusual state of matter, its formation from an arbitrary initial state is presumably extremely improbable. Quantum mechanics provides a way to drastically shorten the odds and fast-track matter to life by exploiting the parallel processing properties of superpositions. There is, however, a deep philosophical issue that must be confronted. I am defining "life" as a certain special state of low probability. Quantum mechanics enables the space of possibilities to be much more efficiently explored than a stochastic classical system. Now, if there are branches of the wave function "containing life" (e.g. a quantum replicator), they will, by assumption, have very small amplitudes. We must therefore explain why the wave function of the system "collapses" onto one of these states of such low intrinsic probability. Expressed differently, how does a quantum superposition recognize that it has "discovered" life and initiate the said collapse? There seems to be an unavoidable teleological component involved: the system somehow "selects" life from the vastly greater number of states that are nonliving.

Actually, the way I have expressed it is an abuse of language. In the standard formulation of quantum mechanics, a quantum system itself never "initiates collapse." The wavefunction collapses as a result of interaction with the environment. One possibility is that replicators are the products of environmental post-selection, perhaps amplified by a quantum feedback loop. The importance of quantum post-selection has only recently been recognized [Aharonov *et al.* (1996)]. The idea is this. The environment serves as a sort of measuring device, and, by hypothesis, it somehow selects for measurement a quantum variable relevant for life. Then even if the amplitude is small, life will be "projected out" of the superposition by the measurement-like interaction. It may even be "steered" towards life by the inverse-Zeno effect. But this implies the environment somehow favours life—that life is "built into" nature in a preordained manner. So an element of teleology remains.

One way to envision the emergence of life by "state exploration" is in terms of a vast decision tree of states (quantum or classical). The root of the tree might correspond to a simple and easy-to-form initial state, which might then evolve to any one of a huge range of possible subsequent states. This can be represented by the tree of states splitting repeatedly into a proliferating number of branches, each branch denoting a possible physical path in state space leading away from the initial state. States of great complexity are represented by branches high up on the tree, and a subset of these branches represents a quantum replicator, or some other state that we may designate as life, or incipient life. The puzzle of life's origin is how the initial simple state "finds" one of the exceedingly rare branches associated with life. Farhi and Gutmann (1998) have compared quantum and classical searches of decision trees, and they find that in some circumstances a quantum search is exponentially faster than a classical search. Their model cannot be immediately applied to the problem of biogenesis, however, because quantum coherence could not possibly be maintained through more than a brief sequence of interactions in any likely prebiotic physical setting. Nevertheless, as the example, of Engel *et al.* (2007) demonstrates, quantum coherence over picosecond timescales is plausible, and leads to an enormous speed-up in the transition to certain otherwise hard-to-attain states.

Our ignorance of the precise nature of the quantum replicator makes it almost impossible to evaluate the probability that one will form as the end product of a quantum search. However, some general points may be made concerning quantum speed-up. If the replicator, or some other quantum structure en route to it, is describable as a local minimum in an energy landscape, with the formation of this unknown system being akin to a phase transition, then quantum mechanics has the ability to enormously enhance the probability of the transition by permitting tunnelling through the relevant potential barrier in the energy landscape. So a possible model of biogenesis is that of a phase transition analogous to bubble nucleation in quantum field theory, where the nucleated lower-energy state is a community of interacting replicators—possibly a large community occupying a mesoscopic region of a condensed matter system. This would constitute a quantum version of Kauffman's concept of an autocatalytic network of molecules [Kauffman (1993)]. Secondly, if the "solution" of the quantum "search" is defined to be a quantum replicator, and if the system does not decohere faster than the replication time, then the replicator should act in a manner similar to a quantum resonance (in view of the fact that the wave function describing the replicator will be amplified by iteration), thus greatly enhancing the probability for a transition to a replicator state.

So far I have been describing the replicator as if it is a physical structure, but the significant point about viewing life in terms of information is that, so long as the information is replicated, the structures embodying that information need not be. In the case of familiar DNA based life, the information represented by the base-pair sequence, and the base-pairs, are replicated together. Thus information replication is tied to structural replication. But at the quantum level there are alternative possibilities. Consider, for example, a cellular automaton, such as the Game of Life—see, for example, Gardner (1970). In this system a group of five clustered cells can form a so-called glider. The glider moves across the array of cells as a coherent (in the classical sense) object, and thus conserves information. However, individual cells are switched on and off, but in a way that preserves the overall pattern. The origins of biological information could belong to this category (perhaps constituting a quantum cellular automaton—see Chapter 12 by Flitney and Abbott in this book). We can imagine a condensed matter system in which a pattern of excitation, or a pattern of spins, or some other quantum variable, might induce transitions in neighbouring quantum states in such a way as to conserve the pattern to high probability, but to "pass on" the excitation, or spin, to adjacent atoms. The "information packet" would thereby be preserved and propagate, until it encounters a suitable quantum milieu in which it will replicate. Then two information packets would propagate away from the interaction region, and so on. Quantum fluctuations in the propagation and replication process would lead in a natural way to "mutations", and to a Darwinian competition between rival information packets.

1.5. Quantum Choreography

An unresolved issue concerning replication is the matter of timing and choreography. In the simplest templating arrangement one can imagine, the formation of complementary base-pairs takes place by random access of molecular components and will proceed at a rate determined by the slower of two processes: the reaction time for pair bonding and the diffusion time of the appropriate molecular or atomic building blocks. In real DNA replication, the base-pairing is incomparably more efficient and faster because it is managed by a large and complex polymerase with complicated internal states. Very little is known about the specifics of the replicase's internal activity, but it seems reasonable to conjecture in relation to its function

that in addition to the normal lowering of potential barriers to facilitate quantum tunnelling (and thus accelerate the process), the replicase also engages in a certain amount of choreography, making sure the right pieces are in the right places at the right times. The concomitant speed-up over the random access process would have a distinct evolutionary advantage.

Although the complexity of the replicase renders its internal workings obscure at this time, one may deploy general arguments to determine whether quantum mechanics might be playing a non-trivial role in the hypothesized choreography, by appealing to the general analysis of quantum time-keeping given by Wigner. As he pointed out, the energy-time uncertainty relation sets a fundamental limit to the operation of all quantum clocks [Wigner (1957); Pesic (1993); Barrow (1996)]. For a clock of mass m and size l, he found

$$T < ml^2/\hbar\,. \tag{1.1}$$

It is noteworthy that, for values of m and l of interest in molecular biology, T also takes values of biological interest, suggesting that some biological systems utilize quantum choreography. Let me give as an example the well-known problem of protein folding, which is a major outstanding problem of theoretical biology [Creighton (1993)]. Consider a peptide chain of N amino acids, which folds into a specific three-dimensional structure. The number of possible final configurations is astronomical, and it is something of a mystery how the chaotically-moving chain "finds" the right configuration in such a short time (typically microseconds). Quantum mechanics could offer an explanation. If the average mass and length of an amino acid are m_o, and a respectively, then Eq. (1.1) yields

$$T < m_o a^2 N^3/\hbar\,, \tag{1.2}$$

suggesting a quantum scaling law for the maximum folding time of

$$T \propto N^3\,. \tag{1.3}$$

It is not clear that the linear dimension is the relevant size parameter when it comes to large proteins. The assumption $l \equiv Na$ in Eq. (1.2) may be justified for small proteins ($N = 80$ to 100) that fold in one step, but larger proteins do not remain "strung out" for a large fraction of the folding process. Instead, they first fold into sub-domains. The opposite limit would be to replace l by the diameter of the folded protein. Assuming it is roughly spherical, this would imply $T \propto N^{5/3}$. The intermediate process of sub-domain folding suggests a more realistic intermediate scaling law of, say,

$$T \propto N^{7/3} \tag{1.4}$$

for large proteins. In fact, a power law of this form has been proposed on empirical grounds [Gutlin *et al.* (1996); Cieplak and Hoang (2003)], with the exponent in the range 2.5 to 3. Inserting typical numerical values from Eq. (1.2), the limiting values of T for a 100 and 1000 amino acid protein are 10^{-3} s and 0.3 s respectively. This is comfortably within the maximum time for many protein folds (typically 10^{-6} s to 10^{-3} s for small proteins *in vitro*), but near the limit for some, hinting that quantum choreography may indeed be taking place in some cases.

Turning now to the polymerase enzyme, this is a molecular motor, or ratchet, powered by ATP and using nucleotides as the raw material for the base pairing. The physics of this system has been studied in some detail for lambda-phage DNA [Goel *et al.* (2003)]. The Wigner inequality (1.1) may be converted to a velocity bound

$$\nu > \hbar/mL\,. \tag{1.5}$$

Using the parameters for the experimentally studied case, taking L to be the length of the DNA (16 μm), and a polymerase mass of about 10^{-19} g, Eq. (1.5) yields a minimum velocity of about 10^{-5}cm s^{-1}. The experimental results show the motor operates at about 100 base pairs per second, which is indeed about 10^{-5} cm s^{-1}, suggesting that in normal operation the motor could be limited by quantum synchronization uncertainty. Experiments demonstrate that applying tension to DNA using optical tweezers decelerates the motor at a rate of about 3 bases per second per pN of applied tension [Goel *et al.* (2003)]. At a tension of about 40 pN the motor stops altogether. (With further stretching of the DNA the motor runs backward). This suggests that the speed of the motor is not determined by the availability of nucleotides or kT (which does not change as a function of tension).

If quantum choreography underlies the efficiency of the polymerase motor, it seems reasonable to suppose that quantum choreography would be even more important in the operation of Q-life. In the absence of a detailed idea of the nature of the hypothetical Q-replicase, it is hard to know what to choose for m and l, but by way of illustration if we take m to be 1000 proton masses and l to be 100 nm then the maximum running time of a quantum clock is a few hundred femtoseconds. Quantum transitions that take longer than about this limit could not be assisted in efficiency by such a Q-replicase. For femtosecond transition rates, however, quantum choreography would seem, at least based on this crude estimate, to offer a good mechanism for instantiating quantum replication.

Acknowledgements

I should like to thank Anita Goel, Gerard Milburn, Sandu Popescu, and Jeff Tollaksen for helpful discussions.

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About the author

Paul C. W. Davies is a theoretical physicist, cosmologist, and astrobiologist. He received his PhD in 1970 from University College London, under Michael Seaton and Sigurd Zienau. At Cambridge, he was a postdoc under Sir Fred Hoyle. He held academic appointments at the Universities of Cambridge, London and Newcastle-upon-Tyne before moving to Australia in 1990, first as Professor of Mathematical Physics at The University of Adelaide, and later as Professor of Natural Philosophy at Macquarie University in Sydney, where he helped establish the NASA-affiliated Australian

Centre for Astrobiology. In September 2006, he joined Arizona State University as College Professor and Director of a new interdisciplinary research institute called Beyond: Center for Fundamental Concepts in Science, devoted to exploring the "big questions" of science and philosophy. Davies' research has been mainly in the theory of quantum fields in curved spacetime, with applications to the very early universe and the properties of black holes, although he is also an expert on the nature of time. His astrobiology research has focused on the origin of life; he was a forerunner of the theory that life on Earth may have originated on Mars.

Davies is the author of several hundred research papers and articles, as well as 27 books, including *The Physics of Time Asymmetry* and *Quantum Fields in Curved Space*, co-authored with his former PhD student Nicholas Birrell. Among his recent popular books are *How to Build a Time Machine* and *The Goldilocks Enigma: Why is the Universe Just Right for Life?* (US edition entitled *Cosmic Jackpot*). He writes frequently for newspapers, journals and magazines in several countries. His television series "The Big Questions", filmed in the Australian outback, won national acclaim, while his theories on astrobiology formed the subject of a specially commissioned one-hour BBC 4 television production screened in 2003 entitled *The Cradle of Life*. In addition, he has also devised and presented many BBC and ABC radio documentaries on topics ranging from chaos theory to superstrings. Davies was awarded the 2001 Kelvin Medal and Prize by the UK Institute of Physics and the 2002 Faraday Award by The Royal Society. In Australia, he was the recipient of two Eureka Prizes and an Advance Australia award. Davies also won the 1995 Templeton Prize for his work on the deeper meaning of science. The asteroid 1992 OG was renamed (6870) Pauldavies in his honour.