

QED-Cavity model of microtubules implies dissipationless energy transfer and biological quantum teleportation

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Abstract

We refine a QED-cavity model of microtubules (MTs), proposed earlier by two of the authors (N.E.M. and D.V.N.), and suggest mechanisms for the formation of biomolecular mesoscopic coherent and/or entangled quantum states, which may avoid decoherence for times comparable to biological characteristic times. This refined model predicts dissipationless energy transfer along such “shielded” macromolecules at near room temperatures as well as quantum teleportation of states across MTs and perhaps neurons.

Keywords: microtubules, cavities, QED, quantum coherence, entanglement, biological quantum computation

1 Introduction

Observable quantum effects in biological matter such as proteins are naively expected to be strongly suppressed, mainly due to the macroscopic nature of most biological entities as well as the fact that such systems live at near room temperature. These conditions normally result in a very fast *collapse* of the pertinent wave-functions to one of the allowed classical states. However, we suggest that under certain circumstances it is in principle possible to obtain the necessary isolation against thermal losses and other environmental interactions, so that *meso- and macroscopic* quantum-mechanical coherence, and conceivably entanglement extending over scales that are considerably larger than the atomic scale, may be achieved and maintained for times comparable to the characteristic times for biomolecular and cellular processes.

In particular, we have shown [1] how microtubules (MTs) [2] can be treated as quantum-mechanically isolated (QED) cavities, exhibiting properties analogous to those of electromagnetic cavities routinely used in quantum optics [3, 4, 5, 6]. Recently, our speculative model has been supported by some indirect experimental evidence. It has been experimentally shown [7], that it is possible to maintain partial entanglement of the bulk spin of a macroscopic quantity of Caesium (Cs) atoms ($N = 10^{12}$), *at room temperature*, for a relatively long time (0.5ms). Note that in this experiment, the large quantity of atoms was of paramount importance in creating and maintaining the entanglement, and even though the gas samples were in constant contact with the environmental heat bath, by using a careful experimental arrangement, Julsgaard et.al. managed to detect the existence of entanglement for a much longer time than one would intuitively expect. Here, we outline the main features of our model of the quantum mechanical properties of MTs (described in detail in [1]), and we exhibit the relevance of the Julsgaard et. al. experiment to our model. A direct consequence of our model for MTs as QED cavities is that virtually every experimentally known QED-cavity-based observation may have an analogue in living MTs and we show this analytically with the specific case of intra- and inter-cellular dissipation-less energy transfer and quantum *teleportation* of coherent quantum states.

Energy transfer across cells, without dissipation, had been first speculated to occur in biological matter by Fröhlich [8]. The phenomenon conjectured by Fröhlich was based on a one-dimensional superconductivity model: a one dimensional electron system with holes, where the formation of solitonic structures due to electron-hole pairing results in the transfer of electric current without dissipation. Fröhlich suggested that, if appropriate solitonic configurations are formed inside cells, energy in biological matter could also be transferred without any dissipation (superefficiently). This idea has lead theorists to construct various models for cellular energy transfer, based on the formation of kink classical solutions [9].

In these early works no specific microscopic models had been considered [9]. In 1993 Sataric et. al. constructed a *classical* physics model for microtubule dynamics [10], in which solitons transfer energy across MTs without dissipation. In the past, we have considered the *quantum aspects* of this one-dimensional model, and developed a framework for the consistent quantization of the soliton solutions[1]. Our work suggested that such semiclassical solutions may emerge as a result of ‘decoherence’ due to environmental interactions, in agreement with ideas in [11].

The basic assumption used in creating the model of ref. [1] was that the building blocks

of MTs, the tubulin molecule dimers, can be treated as elements of Ising spin chains (one-space-dimensional structures). The interaction of each tubulin chain (protofilament) with the neighboring chains and the surrounding water environment has been accounted for by suitable potential terms in the one-dimensional Hamiltonian. The model describing the dynamics of such one-dimensional sub-structures was the ferroelectric distortive spin chain model of ref. [10].

Ferroelectricity is an essential ingredient of the quantum-mechanical mechanism of energy transfer that we propose. We have speculated [12] that the ferroelectric nature of MTs, will be that of *hydrated* ferroelectrics, i.e. the ordering of the electric dipole moment of the tubulin molecules will be due to the interaction of the tubulin dimers' electric dipoles with the ordered-water molecules in the interior and possibly exterior of the microtubular cavities. Ferroelectricity induces a dynamical dielectric 'constant' $\varepsilon(\omega)$ which is dependent on the frequency ω of the excitations in the medium. Below a certain frequency, such materials are characterized by almost vanishing dynamical dielectric 'constants', which in turn implies that electrostatic interactions inversely proportional to ε will be enhanced, and thus become dominant against thermal losses. In the case of microtubules, the pertinent interactions are of the electric dipole type, scaling with the distance r as $1/(\varepsilon r^3)$. For ordinary water media, the dielectric constant is of order 80. In the ferroelectric regime however, this ε is diminished significantly. As a result, the electric dipole-dipole interactions may overcome the thermal losses proportional to $k_B T$ at room temperature inside the interior cylindrical region of MT bounded by the dimer walls of thickness of order of a few Angstroms [1]. The situation is depicted in Figure 1.

It is known experimentally [13], that in a thin exterior neighborhood of MTs there are areas of atomic thickness, consisting of charged ions, which isolate the MT from thermal losses. This means that the electrostatic interactions overcome thermal agitations. It seems theoretically plausible, albeit yet unverified, that such thermally isolated exterior areas can also operate as *cavity regions*, in a manner similar to the areas interior to MTs. At this point it is unclear whether there exist the necessary coherent dipole quanta in the ionic areas. Further experimental and theoretical (simulational) work needs to be done regarding this issue and this is in progress.

Once such an isolation is provided, one can treat the thin interior regions as electromagnetic cavities in a way similar to that of QED cavities¹. QED cavities are well known for their capacity to sustain in their interior coherent modes of electromagnetic radiation. Similarly, one expects that such coherent cavity modes will occur in the thin interior regions of MTs bounded by the protein dimer walls. Indeed, as we discussed in [1], these modes are provided by the interaction of the electric dipole moments of the ordered-water molecules in the interior of MT with the quantised electromagnetic radiation [15, 16]. Such coherent modes are termed *dipole quanta*. It is the interaction of such cavity modes with the electric dipole excitations of the dimers that leads to the formation of coherent (dipole) states on the tubulin dimer walls of MTs. A review of how this can happen, and what *purely quantum* effects can emerge from the QED nature of MTs, will be the main topic of this

¹Note that the role of MT as *waveguides* has been proposed by S. Hameroff already some time ago [14]. In our scenario on the other hand, we are interested in isolated regions inside the MT which play the role of *QED cavities*.

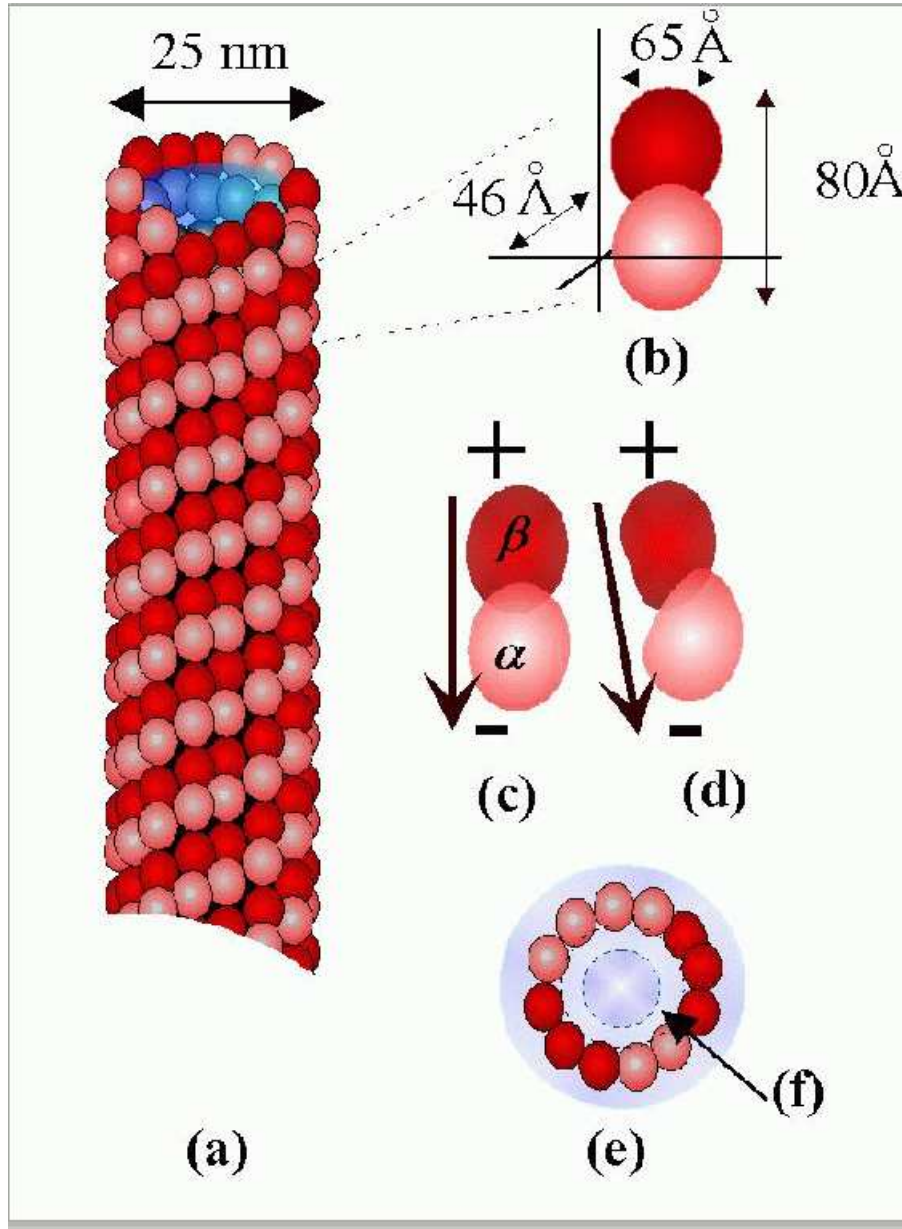


Figure 1: (a) Typical microtubule made of 13 tubulin protofilaments. Each protofilament is displaced vertically from its neighbor a fifth of the dimer vertical height. (b) dimensions of the heterodimer as solved by electron crystallography of zinc-induced sheets [19] note that the MT consists of (c) GTP-tubulin and (d) GDP-tubulin. Arrows indicate the direction of the electric dipole moment for the two conformations. (e) a cross section of the MT showing the surrounding water layer and (f) the thin interior layer that is to be treated as a QED cavity.

communication.

In Section 2 we present a concise exposé of our mechanism [1] that justifies the application of quantum physics to the treatment of certain aspects of MT dynamics. In section 3 we

develop an analogy of our mechanism to the experimental setup used by Julsgaard et. al. In Section 4 we present a straight forward calculation of how quantum teleportation of states can occur in MTs, in direct analogy to the suggester experimental quantum teleportation in optical cavities that has been observed recently [17, 18]. We also draw a parallel between certain geometrical features of MTs such as their ordered structure which obeys a potentially information-encoding code and suggest how this can be exploited for (quantum) error-correction and dense coding. Section 5 contains our conclusions and outlook.

2 Quantum Coherence in Biological Matter?

2.1 Tubulin, Microtubules and Coherent States

Tubulin is a common polar protein found mainly in the cytoskeleton of eukariotic cells which is especially enriched in brain tissue. Many of its properties have been studied both experimentally and theoretically because of its importance in mitosis, its role as the building block of microtubules and its relevance to several diseases including Cancer and Alzheimer's. Measurements [19] have confirmed earlier data suggesting that the tubulin heterodimer has dimensions 46 X 80 X 65 Angstrom [Fig. 1 (b)]. Under normal physiological conditions, tubulin is found as a heterodimer, consisting of two nearly identical monomers called the α - and β - tubulin each of molecular weight of about 55kDalton [19]. MTs are hollow (25nm-outer diameter, 14nm inner diameter) -see Fig. 1 (a) tubes forming the main component of the cytoskeleton and apart from giving shape and support to the cell, they also play a major role in cellular transport and have been hypothesized to be central in cellular information processing. The interior of the MT, seems to contain *ordered water* molecules [1], which implies the existence of an electric dipole moment and an electric field. We stress that the intracellular *ordered water* which is full of proteins and other molecules is different from ordinary water in various respects e.g. as is implied in [20]. It is to be understood that unless otherwise specified, from now on by 'tubulin' we refer to the $\alpha\beta$ -dimer. Free tubulin can self-assemble into MTs both *in vivo* and *in vitro* where the most common arrangement of the tubulin dimers is such that, if one treats them as points, they resemble triangular lattices on the MT surface. The β -tubulin monomer of the heterodimer can bind guanosine 5' triphosphate (GTP) in which case it exists in an energy-rich form that favors polymerization, or it can bind guanosine 5' diphosphate (GDP-tubulin) thus being in an energy-poor form (GDP-tubulin) that favors dissociation. The structure of MTs has been the subject of comprehensive study and it transpires that MTs come in a variety of arrangements the predominant of which is a 5-start, period-13 helical tube of dimers which resembles a corn ear [Fig.1 (a)] made out of 13 offset protofilaments. Certain interesting phenomena arise during the (de-) polymerization of tubulin such as length oscillations, treadmilling etc. generally referred to as 'dynamic instability' and these have been studied extensively [21, 22] but are not directly relevant to our analysis at this stage as such phenomena are suppressed in the remarkably stable axonal neural cytoskeleton. It has been shown that the GDP-GTP exchange (hydrolysis) releases approximately 0.42eV per molecule and is accompanied by a conformational change [23]. This change has been modelled as resulting in a $27^{\circ}42'$ angle [24] between the original line connecting the centers of the α and β monomers and the new

center-to-center line [Fig. 1 (d)]. As a result of this change in the geometry of the tubulin molecule, the orientation of the electric dipole moment also changes magnitude and direction. It has been put forward that each dimer has two hydrophobic protein pockets, containing 2×18 unpaired electrons [2] that have at least two possible configurations associated with the GTP and GDP states of tubulin, which we will call \uparrow and \downarrow electron (or equivalently electric dipole moment) conformations respectively.

Using the fact that a typical 'distance' for the transition between the \uparrow and \downarrow conformations is of order of the distance between the two hydrophobic dimer pockets, i.e. $\mathcal{O}(4 \text{ nm})$, a simplistic estimate of the free tubulin electric dipole moment d can be obtained based on a mobile charge of 36 electrons multiplied by this separation of 4nm giving a magnitude of $d = 2.3 \times 10^{-26} C \cdot m$ (or 700 Debye) while using a more sophisticated molecular simulation, d has been quoted at 1714 Debye [25]. It is evident that an experimentally determined electric dipole moment for the tubulin molecule and its dynamics are important areas of study that have to be undertaken if these studies are to move forward.

If we account for the effect of the water environment that screens the electric charge of the dimers by the relative dielectric constant of the water, which is $\epsilon/\epsilon_0 \sim 80$, we arrive at a value of

$$d_{dimer} \sim 3 \times 10^{-28} \text{ C} \times \text{m} \quad (1)$$

Note that under physiological conditions, the unpaired electric charges in the dimer may lead to even further suppression of d_{dimer} (1).

At physiological pH (=7.2) MTs are negatively charged [26] due to the presence of a 15-residue carboxyl-terminus 'tail' and there have been suggestions that this C-terminus is important in polymerization, protein interactions and perhaps charge conduction [13]. This terminus has not been included in the electron crystallography data of Nogales and Downing [19] so all values concerning the dipole moment are quoted with the understanding that d has been calculated ignoring the effect of the C-terminus. It is also known that at pH 5.6 MTs become neutral. Finally, there have been some preliminary experiments aimed at measuring the electric field around MTs [27, 28, 29] indicating that MTs could be ferroelectric, as we have suggested in our model of [1] and [12]. Note that although the 'caps' of the MT contain both GTP and GDP tubulin, it is well known experimentally [24] that the tubulin comprising the 'trunk' of the MT is GDP-tubulin incapable of acquiring a phosphate and becoming GTP tubulin. However, this does not preclude electric-dipole moment flip wave propagation down the MT, as a flip at the cap can be propagated without phosphorylation or hydrolysis but rather via the mechanism suggested below. In view of this, the value of the yet undetermined electric dipole moment direction flip angle θ_{flip} is much smaller than the $27^\circ 42'$ value for free tubulin. The \uparrow and \downarrow states still exist though, but are hard to observe experimentally as they are not associated with a large-scale geometrical mass shift. Note that virtually all of the alternative suggested MT-based "quantum brain" hypotheses today, fail to take this into account and instead wrongly suggest that θ_{flip} is of the order of 27° and that such large distortions occur in the trunk of the polymerized MT.

In standard models for the simulation of MT dynamics [10], the physical degree of freedom which is relevant for the description of energy transfer is the projection of the electric dipole moment on the longitudinal symmetry axis (x-axis) of the MT cylinder. The θ_{flip} distortion of the \downarrow -conformation leads to a displacement u_n along the x -axis. This way, the effective system

is one-dimensional (spatial), and one has the possibility of being quantum integrable [1].

It has been suggested for quite some time that information processing via interactions among the MT protofilament chains can be sustained on such a system, if the system is considered as a series of interacting Ising chains on a triangular lattice. For such schemes to work, one must first show that the electromagnetic interactions among the tubulin dimers are strong enough to overcome thermal noise. It is due to this problem that such models for intra-neuronal information processing have been criticized as unphysical [30]. We shall return to this issue later. Classically, the various dimers can only be in the \uparrow and \downarrow conformations. Each dimer is influenced by the neighboring dimers resulting in the possibility of a transition. This is the basis for classical information processing, which constitutes the picture of a (classical) cellular automaton.

If we assume (and there is good theoretical basis for such an assumption [1]) that each dimer can in fact find itself in a superposition of \uparrow and \downarrow states a *quantum nature* results. Tubulin can then be viewed as a typical *two-state* quantum mechanical system, where the dimers couple to conformational changes with $10^{-9} - 10^{-11}$ sec transitions, corresponding to an angular frequency $\omega \sim \mathcal{O}(10^{10}) - \mathcal{O}(10^{12})$ Hz. In the present work we assume the upper bound of this frequency range to represent (in order of magnitude) the characteristic frequency of the dimers, viewed as a two-state quantum-mechanical system:

$$\omega_0 \sim \mathcal{O}(10^{12}) \text{ Hz} \quad (2)$$

As we shall see below, such a frequency range is not unusual in biology.

Let u_n be the displacement field of the n -th dimer in a MT chain. The continuous approximation proves sufficient for the study of phenomena associated with energy transfer in biological cells, and this implies that one can make the replacement

$$u_n \rightarrow u(x, t) \quad (3)$$

with x a spatial coordinate along the longitudinal symmetry axis of the MT. There is a time variable t due to fluctuations of the displacements $u(x)$ as a result of the dipole oscillations in the dimers.

The effects of the neighboring dimers (including neighboring chains) can be phenomenologically accounted for by an effective potential $V(u)$. In the model of ref. [10] a double-well potential was used, leading to a classical kink solution for the $u(x, t)$ field. More complicated interactions are allowed in the picture of ref. [1], where we have considered more generic polynomial potentials.

The effects of the surrounding water molecules can be accounted for by a viscous force term that damps out the dimer oscillations,

$$F = -\gamma \partial_t u \quad (4)$$

with γ determined phenomenologically at this stage. This friction should be viewed as an environmental effect, which however does not lead to energy dissipation, as a result of the non-trivial solitonic structure of the ground-state and the non-zero constant force due to the electric field. This is a well known result, directly relevant to energy transfer in biological systems [9].

The effective equation of motion for the relevant field degree of freedom $u(x, t)$ reads:

$$u''(\xi) + \rho u'(\xi) = P(u) \quad (5)$$

where $\xi = x - vt$, v is the velocity of the soliton, $\rho \propto \gamma$ [10], and $P(u)$ is a polynomial in u , of a certain degree, stemming from the variations of the potential $V(u)$ describing interactions among the MT chains [1]. In the mathematical literature [31] there has been a classification of solutions of equations of this form. For certain forms of the potential [1] the solutions include *kink solitons* that may be responsible for dissipation-free energy transfer in biological cells [9]:

$$u(x, t) \sim c_1 (\tanh[c_2(x - vt)] + c_3) \quad (6)$$

where c_1, c_2, c_3 are constants depending on the parameters of the dimer lattice model. For the form of the potential assumed in the model of [10] there are solitons of the form $u(x, t) = c'_1 + \frac{c'_2 - c'_1}{1 + e^{c'_3(c'_2 - c'_1)(x - vt)}}$, where again $c'_i, i = 1, \dots, 3$ are appropriate constants.

A semiclassical quantization of such solitonic states has been considered in [1]. The result of such a quantization yields a modified soliton equation for the (quantum corrected) field $u_q(x, t)$ [32]

$$\partial_t^2 u_q(x, t) - \partial_x^2 u_q(x, t) + \mathcal{M}^{(1)}[u_q(x, t)] = 0 \quad (7)$$

with the notation

$M^{(n)} = e^{\frac{1}{2}(G(x, x, t) - G_0(x, x))} \frac{\partial^2}{\partial z^2} U^{(n)}(z)|_{z=u_q(x, t)}$, and $U^{(n)} \equiv d^n U / dz^n$. The quantity U denotes the potential of the original soliton Hamiltonian, and $G(x, y, t)$ is a bilocal field that describes quantum corrections due to the modified boson field around the soliton. The quantities $M^{(n)}$ carry information about the quantum corrections. For the kink soliton (6) the quantum corrections (7) have been calculated explicitly in ref. [32], thereby providing us with a concrete example of a large-scale quantum coherent state.

A typical propagation velocity of the kink solitons (e.g. in the model of ref. [10]) is $v \sim 2$ m/sec, although, models with $v \sim 20$ m/sec have also been considered [33]. This implies that, for moderately long microtubules of length $L \sim 10^{-6}$ m, such kinks transport energy without dissipation in

$$t_F \sim 5 \times 10^{-7} \text{ sec} \quad (8)$$

Energy will be transferred super-efficiently via this mechanism only if the decoherence time is of the order of, or longer than, this time. We shall see in fact that indeed such time scales are comparable to, or smaller in magnitude than, the decoherence time scale of the coherent (solitonic) states $u_q(x, t)$. This then implies that fundamental quantum mechanical phenomena may be responsible for frictionless, dissipationless super-efficient energy (and signal) transfer and/or transduction across microtubular networks in the cell.

2.2 Microtubules as Cavities

In ref. [1] we have presented a microscopic analysis of the physics underlying the interaction of the water molecules with the dimers of the MT, which is responsible for providing the friction term (4) in the effective (continuum) description. Below we briefly review this scenario.

As a result of the ordered structure of the water environment in the interior of MTs, there appear *collective* coherent modes, the so-called dipole quanta [15]. These arise from the interaction of the electric dipole moment of the water molecule with the quantized radiation of the electromagnetic field [16], which may be self-generated in the case of MT arrangements [33, 1]. Such coherent modes play the role of ‘cavity modes’ in the quantum optics terminology. These in turn interact with the dimer structures, mainly through the unpaired electrons of the dimers, leading to the formation of a quantum coherent solitonic state that may extend even over the entire MT network. As mentioned above, such states may be identified [1] with semi-classical solutions of the friction equations (5). These coherent, almost classical, states should be viewed as the result of *decoherence* of the dimer system due to its interaction/coupling with the water environment [11].

Such a dimer/water coupling can lead to a situation analogous to that of atoms interacting with coherent modes of the electromagnetic radiation in *quantum optical cavities*, namely to the so-called *Vacuum-Field Rabi Splitting* (VFRS) effect [4]. VFRS appears in both the emission and absorption spectra of atoms [5] in interaction with a coherent mode of electromagnetic radiation in a cavity. For our purposes below, we shall review the phenomenon by restricting ourselves for definiteness to the absorption spectra case.

Consider a collection of N atoms of characteristic frequency ω_0 inside an electromagnetic cavity. Injecting a pulse of frequency Ω into the cavity causes a doublet structure (splitting) in the absorption spectrum of the atom-cavity system with peaks at:

$$\Omega = \omega_0 - \Delta/2 \pm \frac{1}{2}(\Delta^2 + 4N\lambda^2)^{1/2} \quad (9)$$

where $\Delta = \omega_c - \omega_0$ is the detuning of the cavity mode, of frequency ω_c , compared to the atomic frequency. For resonant cavities the splitting occurs with equal weights

$$\Omega = \omega_0 \pm \lambda\sqrt{N} \quad (10)$$

Notice here the *enhancement* of the effect for multi-atom systems $N \gg 1$. The quantity $2\lambda\sqrt{N}$ is called the ‘Rabi frequency’ [4]. From the emission-spectrum analysis an estimate of λ can be inferred which involves the matrix element, \underline{d} , of atomic electric dipole between the energy states of the two-level atom [4]:

$$\lambda = \frac{E_c \underline{d} \cdot \underline{\epsilon}}{\hbar} \quad (11)$$

where $\underline{\epsilon}$ is the cavity (radiation) mode polarisation, and

$$E_c \sim \left(\frac{2\pi\hbar\omega_c}{\epsilon V} \right)^{1/2} \quad (12)$$

is the r.m.s. vacuum (electric) field amplitude at the center of a cavity of volume V , and of frequency ω_c , with ϵ the dielectric constant of the medium inside the volume V . In atomic physics the VFRS effect has been confirmed by experiments involving beams of Rydberg atoms resonantly coupled to superconducting cavities [6].

In the analogy between the thin cavity regions near the dimer walls of MTs with electromagnetic cavities, the role of atoms in this case is played by the unpaired two-state electrons

of the tubulin dimers [1] oscillating with a frequency (2). To estimate the Rabi coupling between cavity modes and dimer oscillations, one should use (11) for the MT case.

We have used some simplified models for the ordered-water molecules, which yield a frequency of the coherent dipole quanta ('cavity' modes) of order [1]:

$$\omega_c \sim 6 \times 10^{12} s^{-1} \quad (13)$$

Notably this is of the same order of magnitude as the characteristic frequency of the dimers (2), implying that the dominant cavity mode and the dimer system are almost in resonance in our model of [1]. Note that this is a feature shared by atomic physics systems in cavities, and thus we can apply the pertinent formalism to our system. Assuming a relative dielectric constant of water w.r.t to that of vacuum ϵ_0 , $\epsilon/\epsilon_0 \sim 80$, one obtains from (12) for the case of MT cavities:

$$E_c \sim 10^4 \text{ V/m} \quad (14)$$

Electric fields of such a magnitude can be provided by the electromagnetic interactions of the MT dimer chains, the latter viewed as giant electric dipoles [10]. This suggests that the coherent modes ω_c , which in our scenario interact with the unpaired electric charges of the dimers and produce the kink solitons along the chains, owe their existence to the (quantized) electromagnetic interactions of the dimers themselves.

The Rabi coupling for the MT case then is estimated from (11) to be of order:

$$\begin{aligned} \text{Rabi coupling for MT} &\equiv \lambda_{MT} = \\ \sqrt{\mathcal{N}}\lambda_0 &\sim 3 \times 10^{11} s^{-1} \end{aligned} \quad (15)$$

which is, on average, an order of magnitude smaller than the characteristic frequency of the dimers (2).

In the above analysis, we have assumed that the system of tubulin dimers interacts with a *single* dipole-quantum coherent mode of the ordered water and hence we ignored dimer-dimer interactions. More complicated cases, involving interactions either among the dimers or of the dimers with more than one radiation quantum, which undoubtedly occur *in vivo*, may affect the above estimate.

The presence of such a coupling between water molecules and dimers leads to quantum coherent solitonic states of the electric dipole quanta on the tubulin dimer walls. To estimate the decoherence time we remark that the main source of dissipation (environmental entanglement) comes from the imperfect walls of the cavities, which allow leakage of coherent modes and energy. The time scale, T_r , over which a cavity-MT dissipates its energy, can be identified in our model with the average life-time t_L of a coherent-dipole quantum state, which has been found to be [1]: $T_r \sim t_L \sim 10^{-4}$ sec. This leads to a first-order-approximation estimate of the quality factor for the MT cavities, $Q_{MT} \sim \omega_c T_r \sim \mathcal{O}(10^8)$. We note, for comparison, that high-quality cavities encountered in Rydberg atom experiments dissipate energy in time scales of $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-4})$ sec, and have Q 's which are comparable to Q_{MT} above. The analysis of [1] then yields the following estimate for the collapse time of the kink coherent state of the MT dimers due to dissipation:

$$t_{collapse} \sim \mathcal{O}(10^{-7}) - \mathcal{O}(10^{-6}) \text{ sec} \quad (16)$$

This is larger than the time scale (8) required for energy transport across the MT by an average kink soliton in the models of [10, 33]. The result (16), then, implies that quantum physics is relevant as far as dissipationless energy transfer across the MT is concerned.

In view of this specific model, we are therefore in stark *disagreement* with the conclusions of Tegmark in [30], i.e. that only classical physics is relevant for studying the energy and signal transfer in biological matter. Tegmark's conclusions did not take proper account of the possible isolation against environmental interactions, which seems to occur inside certain regions of MTs with appropriate geometry and properties MT.

We would now like to discuss the feasibility of the above, admittedly speculative, ideas by making a brief report on recent progress made by experimentally demonstrating macroscopic quantum entanglement at room temperature in atomic physics.

2.3 On Ordered Water in Biological Systems

The above scenaria may find some support by independent studies of water in biological matter, which we summarize below. Recent experimental spectroscopic studies of resonant intermolecular transfer of vibrational energy in liquid water [34] have established that energy is transferred extremely rapidly and along many water molecules before it dissipates. This energy is in the form of OH-stretch excitations and is thought to be mediated by dipole-dipole interactions in addition to a yet unknown mechanism which speeds up the transfer beyond that predicted by the so-called Förster expression for the energy transfer rate between two OH oscillators, k .

$$k = T_1^{-1} \left(\frac{r_o}{r} \right)^6 \quad (17)$$

where T_1 is the lifetime of the excited state, r the distance between the oscillators and r_o the Förster radius. The Förster radius, which is a parameter experimentally determined for each material, characterizes the intermolecular energy transfer and has been determined by Woutersen et. al. [34] to be $r_o = 2.1 \pm 0.05$ Angstroms while the typical intermolecular distance (at room temperature) for water is ~ 2.8 Angstrom. It is evident from these data that the energy transfer in pure water will be extremely fast (of order 100ps) and yet experimentally it is determined to be even faster than that. Woutersen *et. al.* speculate that this extremely high rate of resonant energy transfer in liquid water may be a consequence of the proximity of the OH groups in liquid water which causes other, higher-order -uples to also exchange energy. We propose another mechanism to explain the rapidity of the energy transfer, namely kink-soliton propagation. This proposition is based on the phenomenological realization that this is exactly the kind of energy transfer that one would expect to see experimentally as a result of the existence of kink-solitons. It is evident that such a mechanism, regardless of exact origin, is *ideal* for loss-free energy transfer between OH groups located on either different biomolecules or along extended biological structures such as MTs which would be covered (inside and out) with water. Note also that such a mechanism would predict that OH groups in hydrophobic environments would be able to remain in a vibrationally excited state longer than OH groups in hydrophilic environment lending credence to our working assumption that the electrons inside the hydrophobic pockets of the tubulin molecules are sufficiently isolated from thermal noise.

It must be stressed though that such solitonic states in water may not be quantum in origin in the case of microtubules. The 25 nm diameter of the MT is too big a region to allow for quantum effects to be sustained throughout, as we discussed above. Such solitons may be nothing other than the ones conjectured in [35], which may be responsible for the optical transparency of the water interior of MTs. However, such classical solitons in the bulk of the water interior may co-exist with the quantum coherent states on the dimer walls [1].

2.4 Error Correction and Long-lived Quantum Entanglement of Macroscopic Sample at Room Temperature

As we have seen above, under appropriate environmental isolation, it is possible to obtain quantum coherence on *macroscopic populations* of tubulin dimers in microtubule systems, which can be sustained for long enough times so that dissipationless energy and signal (information) transfer can occur in a cell.

In a recent article [7] Julsgaard et. al. describe the macroscopic entanglement of two samples of Cs atoms at room T^o . The entangling mechanism is a pulsed laser beam and although the atoms are far from cold or isolated from the environment, partial entanglement of bulk spin is unambiguously demonstrated for 10^{12} atoms for $\sim 0.5ms$. The system's resilience to decoherence is in fact *facilitated* by the existence of a large number of atoms as even though atoms lose the proper spin orientation continuously, the *bulk* entanglement is not immediately lost. Quantum informatics, the science that deals with ways to encode, store and retrieve information written in qubits has to offer an alternative way of interpreting the surprising resilience of the Cs atoms by using the idea of "redundancy". Simply stated, information can be stored in such a way that the logical (qu)bits correspond to many physical (qu)bits and thus are resistant to corruption of content. Yet another way of looking at this is given in the work by Kielpinski et. al. [36] where they have experimentally demonstrated a decoherence-free quantum memory of one qubit by encoding the qubit into the "decoherence-free subspace" (DFS) of a pair of trapped Berrilium $^9Be^+$ ions. They achieved this by exploiting a "safe-from-noise-area" of the Hilbert space for a *superposition* of two basis states for the ions, thus encoding the qubit in the superposition rather than one of the basis states. By doing this they achieved decoherence times on average an order of magnitude longer.

Both of the above works show that it is possible to use DFS, error correction and high redundancy to both store information and to keep superpositions and entanglements alive for biologically relevant times in macroscopic systems at high temperature.

Thus it may not be entirely inappropriate to imagine that in biological *in vivo* regimes, one has, under certain circumstances, such as specified above, similar entanglement of tubulin/MT arrangements.

3 Possible Implications of Quantum Coherence to the Functioning of Cells

The above raises the question of how such phenomena can affect the functioning of cells. In other words, would the existence of such coherent states and the emergence of quantum mechanical entanglement be somehow useful or beneficial to biological function? Is it then reasonable to propose that in certain cases, natural selection may have favored molecules and cellular structures that exhibited such phenomena? If we accept the notion that according to the laws of quantum physics certain macroscopic arrangements of atoms will exhibit such effects, is it not reasonable then to expect that biomolecules and (by extension) cellular structures and whole cells have 'found' a use for such phenomena and have evolved to incorporate them? We stress that at a given instant in time, the different microtubule coherent states participating in a specific bulk entanglement would be almost identical due to the fact that they are related/triggered by a specific "external agent" (e.g. the passing of a specific train of action potentials.) This is of outmost importance since it increases the system's resilience to decoherence (by entangling a large number of nearly identical states), in addition to facilitating "sharp decision making" (i.e. rapid choice among a vast number of very similar states) as explained in [37] which is presumably a trait favored by natural selection. Here we digress to investigate one possible use of such effects by noting a straightforward application of entanglement to *teleportation* of coherent quantum states across and between cells.

We define teleportation as the complete transfer of the *coherent state* of an MT *without any direct transfer of mass or energy*. This means that the 'receiver' MT finds itself in an identical state to the 'sender' MT. We will demonstrate that given the possibility for entangled states, teleportation between microtubule A and microtubule C can happen as follows:

A coherent state in microtubule A (referred to as simply A and designated as $|\Psi(A)\rangle$) of the (collective) dipole moment(s) being in either of the two classically allowable states with probability amplitude ω_0 and ω_1 can be written as:

$$|\Psi(A)\rangle = \omega_0 |0\rangle + \omega_1 |1\rangle \quad (18)$$

Step 1: The cell finds itself with *microtubule B and microtubule C* -which can be close together or collinear- in an entangled state written as:

$$|\Psi(B, C)\rangle = \frac{1}{\sqrt{2}} \left(|1_B, 0_C\rangle + |0_B, 1_C\rangle \right) \quad (19)$$

The combined state of A,B,C can be written as:

$$|\Psi(A, B, C)\rangle = |\Psi(A)\rangle \otimes |\Psi(B, C)\rangle \quad (20)$$

which upon expanding the outer product can be written as:

$$|\Psi(A, B, C)\rangle = \frac{1}{\sqrt{2}} \left(\omega_0 (|0_A, 1_B, 0_C\rangle + |0_A, 0_B, 1_C\rangle) + \omega_1 (|1_A, 1_B, 0_C\rangle + |1_A, 0_B, 1_C\rangle) \right) \quad (21)$$

We can also express the combined state $|\Psi(A, B, C)\rangle$ in a different basis, known as the “Bell basis”. Instead of $|0\rangle$ and $|1\rangle$, the basis vectors will now be,

$$|\Psi^\pm(A, B)\rangle = \frac{1}{\sqrt{2}} \left(|0_A, 1_B\rangle \pm |1_A, 0_B\rangle \right) \quad (22)$$

and

$$|\Phi^\pm(A, B)\rangle = \frac{1}{\sqrt{2}} \left(|0_A, 0_B\rangle \pm |1_A, 1_B\rangle \right) \quad (23)$$

In this new basis, our state of the three microtubules $|\Psi(A, B, C)\rangle$ is written as:

$$\begin{aligned} |\Psi(A, B, C)\rangle = & \frac{1}{2} \left(|\Psi^+(A, B)\rangle \otimes (\omega_0 |0_C\rangle + \omega_1 |1_C\rangle) + \right. \\ & \left. |\Phi^+(A, B)\rangle \otimes (\omega_0 |1_C\rangle + \omega_1 |0_C\rangle) + |\Psi^-(A, B)\rangle \otimes (\omega_0 |0_C\rangle - \omega_1 |1_C\rangle) + \right. \\ & \left. |\Phi^-(A, B)\rangle \otimes (\omega_0 |1_C\rangle - \omega_1 |0_C\rangle) \right) \end{aligned} \quad (24)$$

This concludes the first step of teleporting the state of MT A to MT C.

Step 2:

Notice that so far, MT A has not been manipulated by the cell, i.e. the coherent state of A which we designated as $|\Psi(A)\rangle = \omega_0 |0\rangle + \omega_1 |1\rangle$ has not been touched. Now the part of the cell containing A and B (let’s call it the “sender part”) makes a ”measurement” -which in our case can be an electromagnetic interaction with a passing action potential or the binding of a MAP molecule. If this “measurement” or forced collapse is done in the Bell basis, on $|\Psi^\pm(A, B)\rangle$ it will project the state in MT C (!) to:

$$|\Psi^\pm(C)\rangle = \langle \Psi^\pm(A, B) | \Psi(A, B, C) \rangle = \omega_0 |0_C\rangle \pm \omega_1 |1_C\rangle \quad (25)$$

similarly

$$|\Phi^\pm(A, B)\rangle \longrightarrow |\Phi^\pm(C)\rangle = \omega_0 |1_C\rangle \pm \omega_1 |0_C\rangle \quad (26)$$

This effectively concludes the teleportation of the state of MT A to MT C with one caveat. There is a probabilistic nature to this process, which means that MT C may receive the exact copy of the state of MT A i.e. $|\Psi^+(C)\rangle$ or it may receive a state which is a unitary transformation away from the original $|\Psi(A)\rangle$ (one of the other three possibilities: $|\Psi^- \rangle$ or $|\Phi^\pm \rangle$). MT C can reproduce the state of MT A if there is a ‘hardwired’ condition that when MT C receives $|\Psi^+ \rangle$ it does nothing further, yet if it receives one of the other three, it performs the correct unitary transformation to obtain the correct state from A. This ‘hardwired’ behavior can be implemented through the use of codes, not unlike the Kōruga bioinformation [38] code that MTs follow.

Teleportation is a direct consequence of the existence of entanglement and can be imagined as the basis of intra- and inter- cellular correlation which leads to yoked function (e.g. intracellular during translation and intercellular during yoked neuron firing). Experiments to check for such teleportation of states can be designed based on the Surface Plasmon

Resonance (SPR) paradigm [39] as applied to sheets of polymerized tubulin immobilized on a dextran-layered gold film.

Note that our use of pure state vectors, $|\Psi\rangle$, to describe the coherent states along a MT arrangement is justifiable since they do not obey the ordinary Schrödinger evolution equation. Instead, they obey the stochastic equations of open systems, of the form discussed in [40]. Nowhere in our proof of teleportation above did we make use of the precise form of the evolution equations. As argued in [40], by using appropriate stochastic (Langevin type) equations one may recover, for instance, the standard Lindblad form of evolution equations for the corresponding density matrices $\rho = \text{Tr}_{\mathcal{M}}|\Psi\rangle\langle\Psi|$, where \mathcal{M} is an appropriate subset of environmental degrees of freedom, non-accessible to the observer.

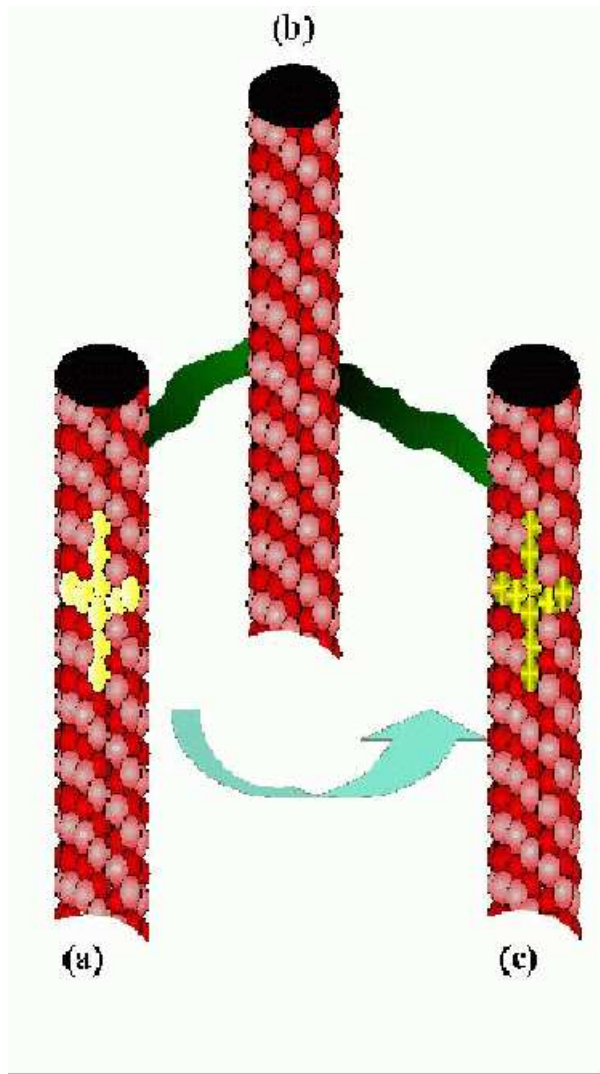


Figure 2: *Schematic of a microtubular quantum teleportation of states. MT a sends its state (represented by a cross) to MT c without any transgfer of mass or energy. Both MT a and MT c are entangled with MT b (entanglement represented by presence of connecting MAPs).*

4 Conclusions and Outlook

In [1] we have put forward a comprehensive model conjecture treating certain regions inside MTs as *isolated* high-Q(uality) QED *cavities*. We also presented a scenario according to which the presence of ordered water in the interior of MTs results in the appearance of electric dipole quantum coherent modes, which couple to the unpaired electrons of the MT dimers via Rabi vacuum field couplings. The situation is analogous to the physics of Rydberg atoms in electromagnetic cavities [4]. In quantum optics, such couplings may be considered as experimental proof of the quantized nature of the electromagnetic radiation. In our case, therefore, if experimentally detected, such couplings would indicate the existence of coherent quantum modes of electric dipole quanta in the ordered water environment of MT, as conjectured in ref. [15, 16], and used here.

To experimentally verify such a situation, one must first try to detect the emergent ferroelectric properties of MTs, which are predicted by this model and are potentially observable. Measurement of the dipole moment of the tubulin dimers is also an important step. A suggestion along these lines has been put forward in ref. [12].

In addition, one should verify the aforementioned vacuum field Rabi coupling (VFRS), λ_{MT} , between the MT dimers and the ordered water quantum coherent modes. The existence of this coupling, could be tested experimentally by the same methods used to measure VFRS in atomic physics [6], i.e. by using the MTs themselves as *cavity environments*, in the way described above, and considering tunable probes to excite the coupled dimer-water system. Such probes could be pulses of (monochromatic) light coupling to MTs. This would be the analogue of an external field in the atomic experiments mentioned above. The field would then resonate, not at the bare frequencies of the coherent dipole quanta or dimers, but at the *Rabi splitted* ones, leading to a double peak in the absorption spectra of the dimers [6]. By using MTs of different sizes one could thus check on the characteristic \sqrt{N} -enhancement of the (resonant) Rabi coupling (10) for MT systems with N dimers.

In the quantum-mechanical scenario for MT dynamics discussed above, as suggested in [1], a quantum-hologram picture for information processing of MT networks emerges. Further, the existence of solitonic quantum-coherent states along the MT dimer walls implies a role for these biological entities as logic gates [41]. Consider, for instance, a node (junction) of three MTs connected by microtubule associated proteins (MAPs) see Fig. 3. The quantum nature of the coherent states makes the junction interaction *probabilistic*. Therefore at tube junctions one is facing a *Probabilistic Boolean Interaction*². The probability for having a solitonic coherent state in a MT branch does depend on its geometric characteristics (such as length). By modulating the length of the tubes and the binding sites of the MAPs one a bias can be introduced between bit states which can affect the probabilistic final outcomes. This has obvious implications for information processing by MT networks.

Such a binary information system can then provide the basic substrate for quantum information processing inside a (not exclusively neural) cell. In a typical MT network, there may be about 10^{12} tubulin dimers. Such a number is macroscopic, and one is tempted to express doubt as to whether, in realistic biological situations, such macroscopic populations of ‘particles’ can be entangled quantum mechanically, with the entangled state being maintained

²We would like to thank Dr. Deeph Chana for suggesting this terminology.

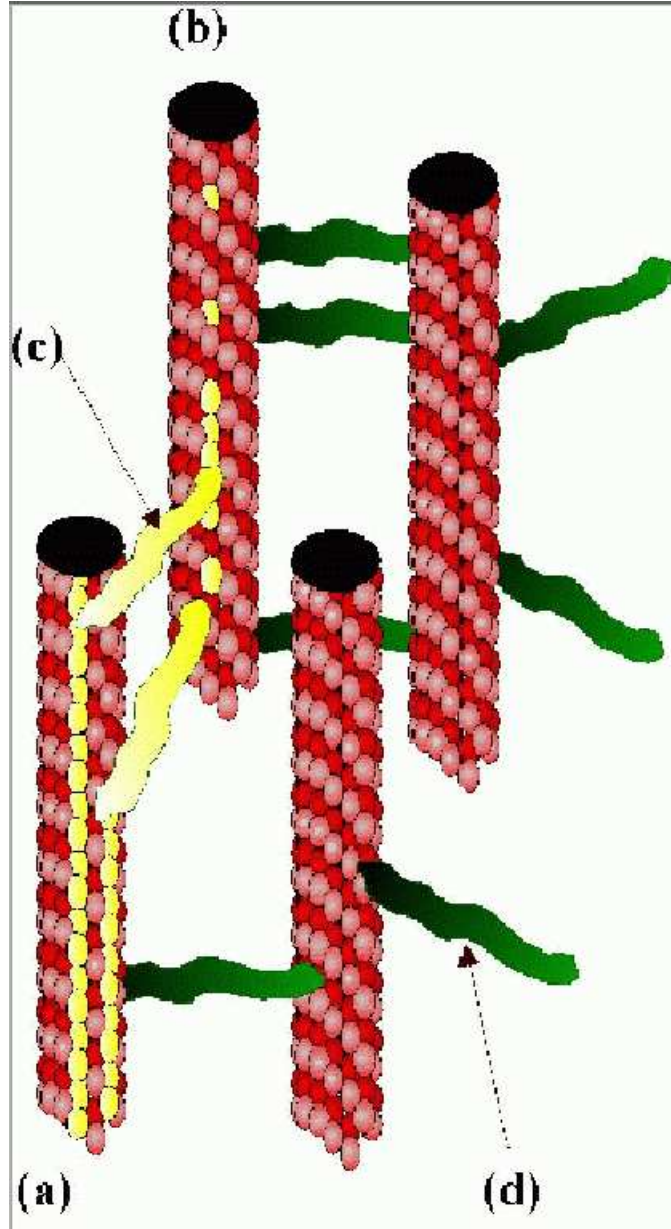


Figure 3: *Example of a microtubular logic gate: A XOR logic gate where “0” is represented by absence of soliton and “1” by presence of soliton. (a) Input MT. (b) Output MT. (c) A MAP transmitting a soliton. (d) A “quiet” MAP. MT a has two solitons travelling, encountering two MAPs that transmit both solitons to MT b (b). In this hypothetical scenario, the solitons arrive out of phase at MT b and cancel each other out. The truth table for XOR reads: $0, 0 \rightarrow 0$; $0, 1 \rightarrow 1$; $1, 0 \rightarrow 1$; $1, 1 \rightarrow 0$. and in this case is realized by MTs if the MAPs are arranged such that each can transmit a soliton independently but if they both transmit, the solitons cancel out.*

for a relatively long period of time. It is worth stressing again that in atomic physics the experiments of ref. [7] have demonstrated *experimentally* the existence of long-lived entangled states of *macroscopic* populations of Cs gas samples, each sample containing 10^{12} atoms. In

such experiments entanglement is generated via interaction with pulses of light. Thus it is not impossible that *in vivo* one has, under certain circumstances as specified above, similar entanglement of MT coherent quantum states.

If it is experimentally confirmed that treating MTs as QED cavities is a fair approximation to their function, then it may not be so foolhardy to imagine that nature has provided us with the necessary structures (microtubules) to operate as the basic substrate for *quantum computation* either *in vivo*, e.g. in the way the brain works, or *in vitro*, i.e. it would allow us to construct quantum computers by using microtubules as building blocks, in much the same way as QED cavities in quantum optics are currently being used in successful attempts at implementing qubits [18].

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