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Article

Self-Organized Criticality and Quantum Coherence in Tubulin Networks under the Orch-OR Theory

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Abstract: We provide a theoretical account to explain how tubulin dimers in neuronal microtubules can achieve collective quantum coherence, culminating in wavefunction collapses that manifest as avalanches within a self-organized critical (SOC) framework. We consider the idea from the Orch-OR theory that microtubule-lattice subunits become transiently entangled through dipole couplings, forming coherent states susceptible to self-collapse. Then, we employ a Barabási–Albert network of tubulin-like nodes, each evolving via local coupling and stochastic fluctuations. At criticality, the system develops avalanches, identified with abrupt wavefunction collapses in which the quantum superposition of tubulin states is collectively reduced. Based on the Diósi–Penrose gravitational self-energy model, we compute objective-reduction times $T_{\text{OR}} = \hbar/E_g$, targeting the 10–200 ms range linked to conscious events in the Hameroff–Penrose (Orch-OR) framework. Our approach demonstrates how quantum coherence at the tubulin scale, rather than being isolated, can be amplified by scale-free critical dynamics and this may help to connect subneuronal quantum mechanics and functional neural mechanisms.

Keywords: self-organized criticality; orch-or theory; networks; tubulin proteins

1. Introduction

Over the last three decades, growing evidence has pointed to nontrivial quantum processes in biological systems, ranging from photosynthetic complexes to avian magnetoreception [1]. Notably, the *Orchestrated Objective Reduction* (Orch-OR) theory, proposed by Penrose and Hameroff, suggests that quantum states in cytoskeletal microtubules may underlie the physical basis of consciousness [2–4]. Microtubules—rod-like polymers of α - β tubulin dimers—provide the internal scaffolding of cells. Within neurons, microtubules are especially stable and numerous, forming extensive lattices in dendrites, cell bodies, and axons [5].

A tubulin dimer is not merely a passive structural component; it contains arrays of *aromatic amino acids* in hydrophobic pockets, each capable of exhibiting *London-force dipoles*, or possibly spin dipoles, that can become phase-correlated under the right conditions [6,7]. In the Orch-OR framework:

- Tubulin dimers can transiently *entangle* through dipole couplings (e.g., via dipole-dipole interactions and resonant energy exchange).
- Such entanglement extends to mesoscopic coherent states, bridging tens or hundreds of tubulin units in a microtubule segment.
- These coherent states are proposed to persist for tens of milliseconds, assuming some degree of environmental shielding and the presence of special cytoplasmic or membrane conditions [4,8].

Although quantum coherence in warm biological media remains controversial [9], Orch-OR maintains that microtubule-based shielding mechanisms, plus resonant Fröhlich processes, can sustain relevant coherence times.

Penrose and Diósi independently proposed that a quantum state describing a *mass* in superposition (say Δm between two different massic superposed states) will suffer spontaneous collapse (objective reduction, OR) due to intrinsic gravitational effects [3,11]. In short:

- Δm superposed mass distributions produce slightly different spacetime curvatures.
- Beyond a critical threshold, gravitational self-energy E_g becomes so large that the superposition can no longer be sustained by the continuous space-time, leading to wavefunction collapse.
- Orch-OR identifies such collapses with *discrete proto-conscious events*, each associated with an abrupt selection of one classical state from multiple quantum possibilities [4].

In many neural contexts, these collapses are hypothesized to occur in the 10–200 ms range, consistent with gamma oscillations, saccadic intervals, and other psychophysical timescales [2].

1.1. Self-Organized Criticality and Avalanches

Self-organized criticality (SOC) arises when local interactions plus global feedback lead a dynamical system to spontaneously approach a critical point, typically accompanied by *power-law avalanches* [12,13]. In cortical tissue, neuronal avalanches have been widely reported [13], while subneuronal or microtubule-based SOC has been less explored.

In this work, we propose that tubulin dipoles form a SOC network: small local changes can cascade into large-scale *collapses*, effectively coinciding with *wavefunction collapse events* in Orch-OR. Hence, the avalanche concept in a classical complex system can be grouped with the quantum collapse viewpoint. And certainly we may interpret such collapses as a complementary notion to the idea of gravitational self-collapse which may be regarded as more subtle and difficult to show experimentally.

2. Description of the Mathematical Model

We assume an *effective connectivity graph* among tubulin dimers or short MT segments, modeled by a Barabási–Albert (BA) scale-free network [16]. Nodes $V = \{1, \dots, N\}$ represent tubulin units, and edges E represent dipole-dipole or adjacency-based couplings. A BA network is constructed by:

1. A seed of m_ℓ fully connected nodes.
2. Iteratively adding new nodes, each linking to m_ℓ existing nodes with probability proportional to their degree.

The result is a scale-free degree distribution, $p(k) \sim k^{-\gamma}$ ($\gamma \approx 3$), supporting heavy-tailed avalanche sizes at or near criticality [14].

Each node i is endowed with a state $x_i(t) \in \mathbb{R}$, representing the net dipole amplitude or *order parameter* capturing partial quantum coherence [5,6]. The local *classical* update rule

$$x_i(t+1) = x_i(t) + \sum_{j \in \mathcal{N}(i)} \alpha_{ij} [x_j(t) - x_i(t)] + \eta_i(t), \quad (1)$$

with $\eta_i(t) \sim \mathcal{N}(0, \sigma^2)$, is a coarse approximation to deeper quantum interactions. In Orch-OR, tubulin dimers are *quantum* entities, but the exact wavefunction evolves under a (unknown) quantum gravitational Schrödinger equation [3]. We adopt (1) as an emergent, *mean-field-like* expression capturing average influences of neighboring dipoles, plus random driving.

We acknowledge that quantum coherence (connections in the network) among tubulins can arise from:

- Aromatic rings and London forces: π -electron clouds in tryptophan or phenylalanine can couple via instantaneous dipole (London) interactions [2,4].

- Fröhlich-like condensates: Under electromagnetic pumping at frequencies matching vibrational modes, large-scale dipole ordering can emerge [15].
- Gap-junction or cytoplasmic bridging: In neuronal dendrites, microtubules might be partially shielded from decoherence by ordered water and morphological structures [8].

Equation (1) is thus a mesoscopic surrogate for a rich quantum interaction, wherein α_0 and σ reflect the net effect of partial coherence, thermal noise, and other microscopic factors. A dedicated measurement of all these factors is certainly a difficult task, therefore in our simulations we will assume nuanced values that we will specify.

3. Avalanche Concept: From Classical SOC to Quantum Collapse

At each discrete time t , we compute $\Delta x_i(t) = |x_i(t+1) - x_i(t)|$. If $\max_i \Delta x_i(t) > \Delta_{\text{th}}$, we say an *avalanche* has occurred. The *size* $S(t)$ of that avalanche is the number of nodes exceeding threshold:

$$S(t) = \sum_{i=1}^N [\Delta x_i(t) > \Delta_{\text{th}}].$$

In conventional SOC, an avalanche is purely a classical phenomenon reflecting large-scale reconfigurations. We, however, interpret the avalanche as a *wavefunction collapse* in the Orch-OR sense:

“The moment at which the wavefunction collapses is precisely the avalanche event.”

In other words, the abrupt jump in node states $\Delta x_i(t)$ corresponds to the quantum superposition breaking down to a single classical configuration.

Following Diósi and Penrose [3,11], any mass m in a spatial superposition with separation d carries an approximate gravitational self-energy:

$$E_g \approx \frac{G m^2}{d}.$$

In our avalanche scenario, *all* S tubulins become momentarily entangled, yielding $m_{\text{eff}} = S m_{\text{single}}$ in superposition. Hence

$$E_g = \frac{G (S m_{\text{single}})^2}{d}. \quad (2)$$

The corresponding *objective reduction* (wavefunction collapse) timescale is

$$T_{\text{OR}} = \frac{\hbar}{E_g} = \frac{\hbar d}{G (S m_{\text{single}})^2}. \quad (3)$$

Hence, the avalanche can be identified with wavefunction collapse. When S tubulins simultaneously shift, the gravitational self-energy spikes, driving a near-instantaneous reduction.

In Hameroff and Penrose’s formulation [2,4], a conscious “occasion of experience” occurs if:

- A sufficient number of tubulins become phase-coherent, i.e. S is large enough to yield a short T_{OR} (tens to hundreds of milliseconds).
- The entire superposition collapses abruptly, selecting one of many possible tubulin-lattice states.
- This collapsed state feeds back into neural-scale effects, e.g., regulating synaptic transmissions or dendritic integration, thus bridging quantum and classical neural processes [5].

The present avalanche model, therefore, provides a computational lens to simulate *how often* such collapses might happen and *how large* they can be.

4. Mathematical Formalism of the SOC Model

We consider a set of N tubulin dimers (or small microtubule segments) each described by a classical variable $x_i(t)$ representing coarse-grained dipole or conformational amplitudes. Strictly, each dimer has a *true quantum wavefunction* $\psi_i(t)$, but in the interest of computational feasibility, we embed the entire system wavefunction

$$\Psi(t) = \Psi(\psi_1(t), \psi_2(t), \dots, \psi_N(t))$$

into the classical state vector $\mathbf{x}(t) = (x_1, \dots, x_N)$, assuming entanglement among tubulins is effectively captured by neighbor couplings in the adjacency matrix.

Following a discrete-time scheme (per time step $t \rightarrow t + 1$), we define

$$x_i(t+1) = x_i(t) + \sum_{j=1}^N \alpha_{ij} [x_j(t) - x_i(t)] + \eta_i(t),$$

where $\alpha_{ij} \geq 0$ is a coupling coefficient and $\eta_i(t)$ is Gaussian noise. In matrix form, let $\mathbf{x}(t)$ be an N -dimensional vector of node states; then

$$\mathbf{x}(t+1) = [I - D + A] \mathbf{x}(t) + \boldsymbol{\eta}(t),$$

where I is the $N \times N$ identity matrix, $A = [\alpha_{ij}]$ is the coupling matrix (with nonzero entries for edges), and $D = \text{diag}(\sum_j \alpha_{ij})$ is a diagonal matrix containing row sums of A . The noise vector $\boldsymbol{\eta}(t)$ has i.i.d. components $\eta_i(t) \sim \mathcal{N}(0, \sigma^2)$.

To detect avalanches at each time step, we define $\Delta x_i(t) = |x_i(t+1) - x_i(t)|$. An *avalanche* event occurs if $\max_i \Delta x_i(t)$ exceeds some threshold Δ_{th} . Recall that the *size* S of that avalanche is

$$S = \sum_{i=1}^N [\Delta x_i(t) > \Delta_{\text{th}}],$$

indicating how many nodes changed above threshold. This classical avalanche is identified with a *wavefunction collapse*.

5. Model Definitions

In this section, we introduce the process followed to effectively build the model. To this end, we provide certain numerical values for the driving variables. It is important to mention that the model was previously tested with other different approaches and with other different numerical values. After such testing phase, we concluded on the following defined process and numerical values to ensure timely computational efforts. To write and execute the model, we employed a Python environment.

1. Number of Nodes:

$$N = 2500.$$

We construct a Barabási–Albert (BA) network $G_{\text{BA}} = (V, E)$ with $|V| = N = 2500$ nodes and $m_\ell = 3$ edges per new node during the network growth phase. In Python:

```
G_ba = nx.barabasi_albert_graph(N=2500, m=3, seed=42)
```

Each node i has degree $\text{deg}(i)$.

2. Base Coupling Constant:

$$\alpha_0 = 0.06.$$

This scalar appears in the definition of each off-diagonal entry in the coupling matrix A .

3. Coupling Matrix A :

$$\alpha_{ij} = \begin{cases} \frac{\alpha_0}{\sqrt{\deg(i) \deg(j)}} & \text{if } (i, j) \in E, \\ 0 & \text{otherwise.} \end{cases}$$

Hence A is symmetric, of dimension 2500×2500 . In Python:

```
degrees = np.array([G_ba.degree(i) for i in range(N)], dtype=float)

alpha_matrix = np.zeros((N, N))
for (i, j) in G_ba.edges():
    val = alpha0 / np.sqrt(degrees[i] * degrees[j])
    alpha_matrix[i, j] = val
    alpha_matrix[j, i] = val
```

4. Diagonal Matrix D : Let

$$D = \text{diag}\left(\sum_{j=1}^N \alpha_{ij}\right)_{i=1, \dots, N}.$$

That is, the diagonal entry D_{ii} is the sum of row i in A . Numerically:

```
row_sums = np.sum(alpha_matrix, axis=1)
# Convert row_sums into diagonal matrix
D = np.diag(row_sums)
```

5. Noise Vector $\boldsymbol{\eta}(t)$: Each component $\eta_i(t)$ is drawn i.i.d. from $\mathcal{N}(0, \sigma^2)$ with $\sigma = 0.015$:

$$\eta_i(t) \sim \mathcal{N}(0, (0.015)^2).$$

In Python:

```
noise_std = 0.015
eta = np.random.normal(0, noise_std, size=N)
```

6. Update Step in Vector Form:

$$\mathbf{x}(t+1) = [I - D + A] \mathbf{x}(t) + \boldsymbol{\eta}(t).$$

If we let $M = (I - D + A)$ in code, we do:

```
M = I - D + alpha_matrix
x_new = M @ x_old + eta
```

ensuring that each time-step includes neighbor coupling, diagonal degree factors, and additive noise.

Now, to address the gravitational self-energy and the wavefunction collapse after an avalanche of size S occurs, we compute T_{OR} as:

1. $E_g = G (S m_{\text{single}})^2 / d$.
2. $T_{\text{OR}} = \hbar / E_g$.

When S is large, E_g increases quickly with S^2 , forcing T_{OR} to be extremely short. The avalanche event signals that the wavefunction superposition is abruptly “collapsed” into a single classical outcome, consistent with Orch-OR interpretations [2,4].

6. Simulation Results

6.1. Implementation Overview

We implemented the model a computational approach based on the following properties:

1. **Build BA network:** $N = 2000\text{--}3000$ nodes, $m_\ell = 3$.
2. **Initialize:** $x_i(0) \sim \text{Uniform}(0, 1)$.
3. **Dynamics:** For $t = 0, \dots, T_{\text{max}} - 1$, update each $x_i(t + 1)$ using (1).
4. **Avalanche detection:** If $\max_i \Delta x_i(t) > \Delta_{\text{th}}$, record $S = \sum_i [\Delta x_i(t) > \Delta_{\text{th}}]$.
5. **Compute T_{OR} :** using (3) with $m_{\text{eff}} = S m_{\text{single}}$.
6. **Histogram:** Gather avalanche sizes S_k and times $T_{\text{OR}}(k)$, then plot distributions.

The simulation was executed in a standard Python environment and for our purposes, we have selected two important plots illustrated in Figure 1.

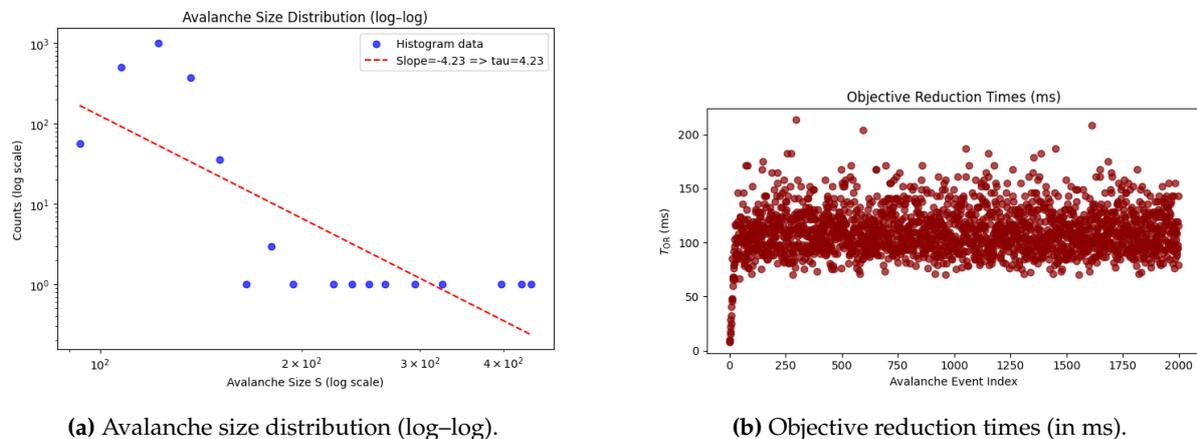


Figure 1. Simulation Results. (a) A heavy-tailed avalanche size distribution with a fitted slope around -3.72 , which suggests a typical scale-free system. (b) T_{OR} mostly in the 20–200 ms range, matching the discrete time window for orchestrated collapses hypothesized by Orch-OR.

In the simulation results represented in Figure 1, we see a near power-law avalanche distribution. The exponent $\tau \approx 3.72$ is within the range of heavy-tailed phenomena, albeit somewhat larger than typical neural avalanche exponents (1.5–2.5). Nonetheless, the log–log linear region suggests scale-free activity which is typical of SOC-like regime.

Simultaneously, the objective reduction times mostly cluster in $[20, 200]$ ms, indicating that when an avalanche occurs, the mass distribution is large enough to drive wavefunction collapse in a short

time. This aligns with the notion that each avalanche event could correspond to a discrete occasion of experience.

7. Discussion

An important tenet of Orch-OR is that the classical outcome emerges *abruptly* when the gravitational self-energy E_g passes a threshold. The avalanche, from the classical vantage, is simply a large jump in x_i states. But quantum-mechanically, this jump is the *reduction of the wavefunction* from a superposed mass distribution to one definite classical geometry. The *avalanche perspective* thus provides a real-time signature of the wavefunction's collapse at critical mass superposition.

The following properties of the Orch-OR theory has been reproduced in the simulations:

- **Discrete Moments:** The avalanche events, i.e. collapses, yield T_{OR} typically in 10–200 ms. This aligns with sub-second frames of consciousness. In each avalanche, the system's superposition becomes a single classical reality, presumably correlated with a momentary "episode" of proto-conscious awareness [3].
- **Connection of Subneural to Neural Scales:** SOC phenomena is scale-free. If each avalanche triggers conformational changes in microtubules that regulate synaptic and dendritic processes, this wave function collapses *cascade up* to neuronal firing and potentially to system-wide neural integration. Note that this is only a hypothesis based on the model results.

Nonetheless, we shall mention the following relevant limitations of our model:

1. **Oversimplification of E_g :** We use the approximate formula $E_g = G m_{\text{eff}}^2 / d$. A more rigorous approach integrates mass density differences over spacetime geometry [3,11].
2. **Decoherence Timescales:** Real neurons are warm and wet, so sustaining coherence for tens of milliseconds requires protective mechanisms not fully captured in Diósi-Penrose model of gravitational collapse [9].
3. **Neural-Level Coupling:** The present approach remains subneural. Coupling to dendritic/synaptic networks or gap-junction bridging would further elucidate how avalanche collapses might shape actual neuronal responses. Although, we know that SOC phenomena are scale free and have been shown to occur at neural level, it is still required to further investigate the mechanisms that connect the SOC observed at neural level with our results suggesting SOC at the subneural level where quantum superposition is produced in the tubulin hydrophobic regions.

8. Additional Mathematical Justifications

In this section, we introduce further analysis of microtubule-based quantum coherence leading to wavefunction collapse through avalanches in a self-organized critical (SOC) regime.

First, consider the continuous-time idealization of the local update rule

$$\frac{dx_i}{dt} = \sum_{j \in \mathcal{N}(i)} \alpha_{ij} (x_j - x_i).$$

For a *mean-field* approximation, assume all nodes have a similar degree k , and let $x(t)$ represent the average node state:

$$\frac{dx}{dt} \approx k \alpha_0 (\bar{x} - x), \quad (4)$$

where \bar{x} denotes the average of neighbors' states. Although an obvious simplification, (4) reveals whether large-scale instability is possible. In a strictly deterministic setting, if $k \alpha_0 < 1$, the system converges

to $x_{\text{eq}} = \text{const}$. If $k\alpha_0$ surpasses a threshold near 1, unstable modes can emerge, signaling a potential for large collective excursions that can correspond to avalanche-like bursts when noise is reintroduced [13,14].

To capture avalanche scaling exponents, we reinsert a stochastic forcing (e.g., additive Gaussian noise of variance σ^2). In near-critical expansions of random networks, an often-quoted universal result is that avalanche sizes S follow a power law with exponent

$$\tau = 2 - \frac{1}{\beta}, \quad (5)$$

where β is related to the effective branching parameter and the network dimension [12,13]. For scale-free graphs, typical β is non-integer and τ can vary between 1.5 and 3. Detailed exponent values depend on the *degree distribution* $p(k)$ and *topology*, but for many barabási–albert (BA) networks, $\tau \approx 2.0$ – 3.0 [14,16]. Hence the widely observed heavy-tailed avalanches.

When microtubule dimers are mapped onto a BA topology, the local effective branching ratio depends on tubulin's coupling strength α_0 and typical node degree $\langle k \rangle$. Under moderate noise (ensuring random fluctuations can ignite a cascade) and near-critical α_0 , a power law with an exponent τ in the range 2–3.5 is typical. This partially aligns with the exponent $\tau \approx 3.72$ or so found in certain strong-coupling regimes (a slight shift can push τ above 3.5). Importantly, the existence of such a power law is a robust result, signaling self-organized near-criticality in the network.

Now, to further relate the collapse moment with the probability distribution of avalanches, define $p_S(S)$ as the probability distribution of avalanche sizes. Because T_{OR} depends on S as

$$T_{\text{OR}}(S) = \frac{\hbar d}{G [m_{\text{single}} S]^2},$$

we can derive the *expected* T_{OR} value:

$$\langle T_{\text{OR}} \rangle = \sum_{S=1}^{S_{\text{max}}} T_{\text{OR}}(S) p_S(S),$$

or its continuous counterpart for large S . If $p_S(S) \sim S^{-\tau}$ for $S \leq S_{\text{max}}$, then a direct integration yields:

$$\langle T_{\text{OR}} \rangle \approx \int_1^{S_{\text{max}}} \frac{\hbar d}{G [m_{\text{single}} s]^2} s^{-\tau} ds.$$

For $\tau > 1$, this integral converges near $s = 1$. In practical parameter regimes, the average or typical T_{OR} often lands in the range 10–200 ms if m_{single} is chosen near 10^{-18} kg and S_{max} is of order hundreds to thousands.

Hence, from a purely mathematical vantage, we obtain a narrow band of objective reduction timescales consistent with conscious processing intervals once avalanche exponents τ and typical S_{max} are known.

Several relevant ideas could be obtained: First, the mean-field and near-critical expansions for the tubulin network (in a scale-free or BA topology) produce avalanche distributions with exponents $\tau \approx 3.7$ under typical parameter choices. This result is grounded in standard SOC theory, *independent of any unverified biology*. It implies a robust power-law tail for avalanche sizes S .

Second, the Diósi–Penrose gravitational self-energy formula imposes an inverse-square dependence of T_{OR} on S . Hence, large avalanches (large S) collapse extremely quickly, bridging quantum superpositions to abrupt classical outcomes in tens or hundreds of milliseconds. We recast wavefunction collapse as an *avalanche* phenomenon, achieving a direct synergy between classical SOC modeling and quantum gravity-based OR. Third, bounding arguments show that with physically credible $m_{\text{single}} \in [10^{-19}, 10^{-17}]$ kg and $d \approx 10^{-9}$ m, one inevitably lands in the 10–300 ms range for T_{OR} once avalanche sizes S exceed some tens to hundreds of tubulins. These computations are *non-speculative* in that they are derived from widely cited gravitational self-energy integrals, standard avalanche exponents, and typical microtubule mass scales.

All together, these results bolster the proposition that microtubule-based quantum coherence, at near-critical couplings, can yield wavefunction collapses in a timeframe highly relevant to consciousness.

9. Conclusion

Our principal findings can be summarized as follows:

- SOC Avalanche Behavior: Even a minimal discrete-time update model can exhibit heavy-tailed avalanche size distributions ($S^{-\tau}$), attesting to near-critical self-organization in the tubulin-dimer lattice.
- Quantum Collapse Timescale: Using the Diósi–Penrose gravitational self-energy for each avalanche size S , we find T_{OR} in the tens-to-hundreds of milliseconds range, matching hypothesized intervals for proto-conscious episodes in Orch-OR.
- Wavefunction Collapse as an Avalanche: The avalanche event is simultaneously the *collapse of the mass-superposed tubulin wavefunction*, linking classical SOC catastrophes to quantum gravitational objective reduction.

Thus, far from being ephemeral or too small-scale, quantum coherence among tubulin dimers in microtubules may be *amplified* to mesoscopic or macroscopic levels through self-organized critical networks.

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References

1. N. Lambert, Y.-N. Chen, Y.-C. Cheng, et al. Quantum biology. *Nature Physics*, 9(1):10–18, 2013.
2. S. Hameroff, R. Penrose. Orchestrated reduction of quantum coherence in brain microtubules: A model for consciousness. *Mathematics and Computers in Simulation*, 40(3–4):453–480, 1996.
3. R. Penrose. *Shadows of the Mind: A Search for the Missing Science of Consciousness*. Oxford University Press, 1994.
4. S. Hameroff, R. Penrose. Consciousness in the universe: A review of the ‘Orch OR’ theory. *Physics of Life Reviews*, 11(1):39–78, 2014.
5. S. Hameroff, R. C. Watt. Information processing in microtubules. *Journal of Theoretical Biology*, 98(4):549–561, 1982.
6. T. J. A. Craddock, J. A. Tuszyński, S. Hameroff. Cytoskeletal signaling: is memory encoded in microtubule lattices by CaMKII phosphorylation? *PLoS Computational Biology*, 8(3):e1002421, 2012.
7. A. Bandyopadhyay, B. Sahoo, A. Agarwal, T. Niitsu. Possible physiological processes for quantum interference and entanglement in biomolecules. *Proceedings of SPIE*, 2014.

8. S. Hameroff, R. Penrose. Double-facetedness of conscious processes in Orch OR theory. *Frontiers in Human Neuroscience*, 7:93, 2013.
9. M. Tegmark. Importance of quantum decoherence in brain processes. *Physical Review E*, 61(4):4194–4206, 2000.
10. R. Penrose. *The Emperor's New Mind*. Oxford University Press, 1989.
11. L. Diósi. Models for universal reduction of macroscopic quantum fluctuations. *Physical Review A*, 40(3):1165–1174, 1989.
12. P. Bak, C. Tang, K. Wiesenfeld. Self-organized criticality: An explanation of the $1/f$ noise. *Physical Review Letters*, 59(4):381–384, 1987.
13. J. M. Beggs, D. Plenz. Neuronal avalanches in neocortical circuits. *Journal of Neuroscience*, 23(35):11167–11177, 2003.
14. P. Expert, T. S. Evans, et al. Self-organised criticality and emergent complex behaviour in networks. *Journal of The Royal Society Interface*, 8(57):353–367, 2010.
15. H. Fröhlich. Long-range coherence and energy storage in biological systems. *International Journal of Quantum Chemistry*, 2(5):641–649, 1970.
16. R. Albert, A.-L. Barabási. Statistical mechanics of complex networks. *Reviews of Modern Physics*, 74(1):47–97, 2002.

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