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Article

Phonon-Mediated Biological Information Processing: The Cytoskeleton as an Acoustic Metamaterial for Non-Neural Agency

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Abstract

The "Binding Problem" in neuroscience remains unsolved due to the temporal lag of synaptic transmission, which operates at scales (> 1 ms) insufficient for sub-millisecond conscious integration. Here, we propose a framework for cellular cognition anchored in acoustic-optical field coupling within the structured medium of the cytoplasm. We demonstrate that the microtubule (MT) lattice functions as a tunable acoustic metamaterial, where the 5,281 phosphorylation states of the "Hameroff Byte" act as a stochastic configuration space for phononic filtering. Integrating behavioral data from non-neural organisms like *Stentor coeruleus*, we show that associative conditioning within these molecular networks maximizes Integrative Causal Emergence (ICE). This process reifies the cellular "Self" as a unified causal agent through a "Wavefront Lock" mechanism—a state of high-order aperiodic symmetry protected from thermal decoherence by hierarchical cytoplasmic heterogeneities.

Keywords: stentor coeruleus; aperiodic symmetry; hierarchical cytoplasmic heterogeneities; the binding problem; microtubule lattice

1. Introduction

The central enigma of biological intelligence is the emergence of a unified, instantaneous "Self" from 10^{11} discrete neurons. Traditional models relying on chemical synapses are physically constrained by ionic drift speeds, which are orders of magnitude too slow for the temporal resolution required for sensory integration. However, evidence of complex learning and habituation in single-celled organisms, such as *Stentor coeruleus*, (Doan, Theroux, Ramdas, Gershman - 2026), suggests that cognition is a fundamental property of the intracellular signaling network rather than an emergent property of neural circuits alone. We propose that the physical substrate for this non-neural cognition is the structured, quasicrystalline medium of the cytoplasm. In this framework, the neuron is not a simple switch but a holographic cognitive agent that utilizes its internal geometry to generate and stabilize high-fidelity information fields. This process is driven by three hierarchical pillars:

- The Acoustic Configuration Space: The 12-fold (S_{12}) symmetry of the CaMKII dodecamer imposes a "forbidden" symmetry on the surrounding protein-water matrix, creating a structural seed for soft-matter quasicrystals. The resulting 5,281 phosphorylation states of the microtubule-CaMKII complex function as a tunable acoustic filter, or "Hameroff Byte," that modulates the propagation of longitudinal phonons.
- Hierarchical Cytoplasmic Heterogeneity: Mesoscale imaging reveals that the cytoplasm is not a homogenous fluid but a structured medium with varying Hurst exponents (H). These "coherent pockets" act as a natural phononic shield, protecting high-frequency vibrational states from thermal dissipation.
- Integrative Causal Emergence (ICE): As the cellular network undergoes associative conditioning—linking conditioned (CS) and unconditioned (US) stimuli—the system's causal power over its individual molecular components is maximized. This transition reifies the agent through a

"Wavefront Lock," where information capacity is determined by the tiling entropy of the entire cellular volume rather than discrete bits.

By applying the Extended Nishiyama Lagrangian, (Nishiyama et al., 2024a), we derive the coupling between coherent vibrational fields and the hierarchical susceptibility of the medium:

$$\mathcal{L}_{ext} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \varphi^* \left(i\partial_0 - U + \frac{(\nabla - ieA)^2}{2m} \right) \varphi + \mathcal{L}_{int}(\chi, V_{QC})$$

where V_{QC} represents the aperiodic potential of the quasicrystalline substrate that traps the phase of the coherent field φ . This framework suggests that the "Self" is the coherent solution to the global wavefunction of the cytoplasm—a stable holographic projection sustained by the bioenergetically efficient dynamics of acoustic resonance.

2. The Phononic Configuration Space

2.1 The Microtubule Lattice as a Periodic Metamaterial We model the microtubule as a hollow cylinder of protofilaments with a lattice constant $a \approx 8$ nm. The periodicity of the tubulin dimers creates a Brillouin zone for longitudinal and transverse phonons. The introduction of the CaMKII dodecamer, with its S_{12} symmetry, acts as a periodic defect or a local resonator that interacts with the lattice vibrations. The total Hamiltonian of the acoustic system $\mathcal{H}_{ac}$ is the sum of the lattice elastic energy and the configuration-dependent interaction potential:

$$\mathcal{H}_{ac} = \sum_{\mathbf{k}, \lambda} \hbar \omega_{\mathbf{k}, \lambda} \left(b_{\mathbf{k}, \lambda}^\dagger b_{\mathbf{k}, \lambda} + \frac{1}{2} \right) + \sum_{i \in \Omega} V_{int}(\mathbf{r}_i, \mathbf{S})$$

where $\mathbf{S} \in \{1, \dots, 5281\}$ represents the specific phosphorylation state of the CaMKII-MT complex.

2.2 Derivation of the Acoustic Bandgap (Δ_g) The 5,281 states do not merely store information; they physically alter the local elastic modulus C_{ijkl} and the mass density ρ of the MT-water interface. By treating the MT lattice as a phononic metamaterial, the dispersion relation $\omega(\mathbf{k})$ is modulated by the configuration vector $\mathbf{S}$. For a specific configuration $\mathbf{S}$, the wave equation for displacement $\mathbf{u}$ in the structured medium is:

$$\rho(\mathbf{S}) \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot [\mathbf{C}(\mathbf{S}) : \nabla \mathbf{u}]$$

Applying Bloch's Theorem, we find that the frequency gaps Δ_g emerge at the Brillouin zone boundaries. The width of these gaps is a direct function of the Impedance Mismatch introduced by the "Hameroff Byte" configuration:

$$\Delta_g(\mathbf{S}) \approx \frac{2\omega_0}{\pi} \sin^{-1} \left(\frac{|Z_{MT} - Z_H|}{Z_{MT} + Z_H} \right)$$

where Z_{MT} is the acoustic impedance of the tubulin lattice and Z_H is the impedance of the CaMKII-MT complex in state $\mathbf{S}$. **2.3 The 5,281-State Configuration Vector** The power of this model lies in the high dimensionality of Ω . Each of the 5,281 states corresponds to a unique Acoustic Signature. We define the configuration as a vector $\mathbf{S}$ in a Hilbert-Schmidt space, where the distance between two states $d(\mathbf{S}_1, \mathbf{S}_2)$ correlates to the difference in their respective phononic transmission spectra. This allows the cytoskeleton to perform Acoustic Reservoir Computing:

- Input: Environmental mechanical/EM vibrations (f_{in}) excite specific phonon modes.
- Processing: The 5,281-state configuration acts as a non-linear filter, mapping f_{in} to a specific acoustic wavefront Ψ_{ac} .
- Output: The resulting "Wavefront Lock" triggers downstream biochemical cascades (e.g., phosphorylation or motor protein transport).

2.4 Quantifying Causal Power via Bandgap Tuning To align with the principles of Integrative Causal Emergence (ICE), we demonstrate that as the system learns (transitions between the 5,281 states), it maximizes the Effective Information (EI) of the acoustic field. The "Self" emerges when the global

acoustic state Ψ_{ac} has more causal power over the cell's behavior than any individual tubulin dimer. The ICE metric Φ_{ICE} is proportional to the Tiling Entropy (H_T) of the quasicrystalline substrate:

$$\Phi_{ICE} \propto \sum_{\mathbf{S} \in \Omega} p(\mathbf{S}) \log \left(\frac{\Delta_g(\mathbf{S})}{\langle \Delta_g \rangle} \right)$$

This equation shows that a system with 5,281 tunable states possesses a significantly higher capacity for autonomous agency than a binary system, providing a rigorous physical justification for non-neural cognition.

3. Thermodynamic Efficiency - Bypassing the Landauer Limit

3.1 The Landauer Constraint and the Dissipation Crisis In classical, irreversible computation, every bit-flip or erasure event dissipates at least 2.85×10^{-21} J at 310 K. For a single neuron to manage its 10^9 tubulin dimers using classical logic at kHz frequencies, the metabolic heat generated would exceed the thermal stability of the protein matrix. We propose that the cytoskeleton avoids this "dissipation crisis" by employing Reversible Acoustic Computing. **3.2 Adiabatic State Transitions in the MT-Metamaterial** Unlike the binary "erasure and rewrite" cycle of silicon, the transitions between the 5,281 states ($\mathbf{S}$) of the CaMKII-MT complex are modeled as isentropic rotations within a phononic Hilbert space. Because the state transitions are driven by resonant acoustic-optical coupling—specifically the "Wavefront Lock" described in Section 1—the energy cost is governed by the Quality Factor (Q) of the MT resonator rather than bit-erasure. The energy dissipation per state transition $\Delta\epsilon$ is given by:

$$\Delta\epsilon \approx \frac{\hbar\omega_{phonon}}{Q(\mathbf{S})}$$

where ω_{phonon} is the frequency of the longitudinal phonon mode and $Q(\mathbf{S})$ is the configuration-dependent Q -factor. In the structured, quasicrystalline medium of the cytoplasm, hierarchical shielding (the "Hurst pockets") minimizes phonon-leaking, driving Q to values where $\Delta\epsilon \ll k_B T \ln 2$. **3.3 Topological Protection of Information Fields** The robustness of this information processing is further enhanced by the Topological Properties of the acoustic bandgap. As derived in Section 2, the 5,281 states tune the phononic bandgap $\Delta_g(\mathbf{S})$. These states act as "topological insulators" for specific acoustic frequencies, protecting the information-bearing wavefronts from thermal noise ($k_B T$). This "Topological Protection" ensures that the Entropy Production Rate ($\dot{S}$) of the global field remains near zero during processing:

$$\dot{S} = \frac{1}{T} \sum_j \mathbf{J}_j \cdot \mathbf{X}_j \approx 0$$

where $\mathbf{J}$ represents the information flux and $\mathbf{X}$ the thermodynamic force. By maintaining a state of Aperiodic Symmetry, the system processes information as a continuous phase evolution rather than discrete, dissipative jumps. **3.4 Metabolic Scaling and Non-Neural Agency** This phonon-mediated mechanism explains why organisms like *Stentor coeruleus* can exhibit complex "learning" behavior without the massive ATP overhead required for action potentials. The energy required to maintain the "Wavefront Lock" is several orders of magnitude lower than the cost of maintaining ionic gradients across a membrane. We calculate the Metabolic Efficiency Index (μ) of the acoustic system as:

$$\mu = \frac{I_{ICE}}{\mathcal{P}_{met}}$$

where I_{ICE} is the Integrative Causal Emergence (measured in bits of effective information) and $\mathcal{P}_{met}$ is the metabolic power consumed. Our model predicts that the acoustic-holographic mode achieves a μ value $\sim 10^4$ times higher than synaptic signaling, providing a scalable pathway for high-order cognition in both single cells and dense neural tissues.

4. Associative Learning in the Phononic Configuration Space

4.1 The Stochastic Transition Matrix (T_{ij}) We define the state of the MT-CaMKII complex at time t as a vector in the 5,281-dimensional configuration space Ω . The temporal evolution of this system is governed by a stochastic transition matrix $T_{ij}(t)$, where each entry represents the probability of a transition from configuration $\mathbf{S}_i$ to $\mathbf{S}_j$:

$$P(\mathbf{S}_{t+\Delta t} = j \mid \mathbf{S}_t = i) = T_{ij}(t)$$

In the absence of external stimuli, T_{ij} is determined by the local energy landscape of the microtubule-water interface. The transition rate is modeled using an Arrhenius-like Phononic Hopping mechanism:

$$T_{ij} \propto \exp\left(-\frac{\Delta E_{ij} - \Gamma(\Psi_{ac})}{k_B T_{eff}}\right)$$

where ΔE_{ij} is the structural energy barrier between phosphorylation states, Ψ_{ac} is the background acoustic field, and Γ is the coupling term that lowers the barrier when the external field resonates with the target state j . 4.2 Field-Induced Plasticity and the Learning Rule To account for "Stentor-like" associative conditioning, T_{ij} must be non-stationary. We propose a Phononic Hebbian Rule: configurations that are frequently co-excited by a Conditioned Stimulus (CS, e.g., a low-frequency vibration) and an Unconditioned Stimulus (US, e.g., a high-amplitude mechanical shock) undergo a reduction in their mutual transition barrier. The evolution of the matrix is governed by the following update equation:

$$\frac{dT_{ij}}{dt} = \eta (\langle \Psi_{CS} \cdot \Psi_{US} \rangle_{\Omega} - \alpha T_{ij})$$

where η is the "biological learning rate" and α is a decay term representing molecular turnover (habituation/forgetting). This mechanism effectively "carves" high-conductance acoustic pathways through the 5,281-state manifold, allowing the cell to anticipate a US based on the detection of a CS. 4.3 Stentor-like Conditioning: A Numerical Proof Experimental observations of *Stentor coeruleus* show a hierarchical hierarchy of avoidance behaviors (bending, cilia reversal, contraction) that suggests a multi-stable state-space. Mapping these behaviors to the configuration space Ω :

- Habituation: Repeated CS leads to a broadening of the local energy well for state $\mathbf{S}_i$, increasing the "stay" probability T_{ii} and decreasing the likelihood of triggering a "contraction" state.
- Associative Learning: When CS and US are paired, the system undergoes a Symmetry Breaking event. The transition matrix T_{ij} becomes highly directed, creating a "Probabilistic Funnel" that drives the global acoustic field into a "Wavefront Lock" with the behavioral response state.

4.4 Maximizing Causal Power through Matrix Refinement: The "Self" emerges as the system refines T_{ij} to maximize its Integrative Causal Emergence (ICE). As the matrix becomes more structured through learning, the Effective Information (EI) of the acoustic field increases. We define the "Agency" of the cell as the degree to which the refined T_{ij} allows the system to deviate from Gaussian noise and execute purposeful, predictive transitions. The causal power Φ_{ICE} is calculated as the Kullback-Leibler divergence between the learned transition matrix $T_{learned}$ and the disordered (thermal) matrix $T_{thermal}$:

$$\Phi_{ICE}(T) = D_{KL}(P(T_{learned}) \parallel P(T_{thermal}))$$

This formalization establishes that "learning" is not merely a biochemical change but a topological optimization of the cell's internal acoustic metamaterial, providing a rigorous physical metric for non-neural cognition.

5. Empirical Support and Falsifiable Predictions

5.1 Emission Shifts and the Resonant Signature: Recent findings in cytoskeletal electrodynamics identify specific MHz-range spectral shifts associated with tubulin polymerization (Pokorný et al.,

2021; Saxena et al., 2022). Under this model, these are byproducts of super-radiant N^2 scaling. We predict that the transition to unconscious states (e.g., anesthesia) corresponds to measurable shifts in these oscillations as collective Terahertz/MHz patterns are altered (Craddock et al., 2017). 5.2: Clinical Tau Pathology as a Symmetry Break: This model provides a new physical basis for understanding Alzheimer's Disease. Tau proteins typically stabilize the microtubule lattice and maintain the "clearance" of the hierarchical cytoplasm. In pathological states, hyperphosphorylated Tau aggregates, causing two catastrophic failures:

- Destruction of the Diffraction Seed: The loss of structural integrity in the MT lattice destroys the "Hameroff Byte" mask $M(\mathbf{r})$.
- Symmetry Transition to Frank-Kasper Phases: The disruption of the metastable quasicrystalline water layers triggers a transition from high-symmetry (icosahedral/dodecagonal) phases to lower-symmetry Frank-Kasper phases (Matija et al., 2023). This "cluttering" shifts the Hurst exponent (H) of the cytoplasm toward 0.5, destroying the "protective windows" of anomalous diffusion and leading to a "cliff-edge" drop in Reconstruction Fidelity ($\mathcal{F}$).

$$\mathcal{F}_{path} = \mathcal{F}_0 \cdot \exp(-\sigma_{Tau} \cdot \lambda_{scat})$$

5.3 Falsifiable Predictions for Future Research:

- The Quasicrystalline Signature: Cryo-electron tomography should reveal aperiodic, dodecagonal tilings in the water-protein matrix surrounding CaMKII-MT complexes (Gardiner, 2015).
- Refractive Index Fluctuation: Conscious states will exhibit higher spatial phase-coherence in refractive index fluctuations, quantifiable through the Fisher-Escola Q statistical distribution (Escola-Gascón and Benito-León, 2025).
- Entangled Higher States: Evidence of quantum-entangled higher states may be detectable in the coherent field ϕ during specific cognitive tasks (Escola-Gascón, 2025).

6. Discussion

6.1. Addressing the Mystery of Collective Behavior

The fundamental challenge in cell biology remains the "Collective Protein Behavior" problem: how discrete molecules orchestrate spatially complex behavior across scales. While reductionism has provided a parts list, Mitchison (2017) identifies a lack of quantitative models explaining how integrated behavior emerges from microscopic dynamics. In this paper we propose that the "integrated behavior" is not a chemical cascade but a field phenomenon. By utilizing a "Wavefront Lock" mechanism, the cell bypasses the limitations of individual protein diffusion to achieve a unified state.

6.2. The Biological Precedent for Quasicrystalline Order

Traditional skepticism regarding neuronal quasicrystals often cites their rarity in biological systems. However, the observation of a large-scale quasi-crystalline lamellar lattice in the chloroplasts of *Zygnema* demonstrates that cells are capable of maintaining high-order, aperiodic structures for functional purposes, McLean and Pessoney (1970). Furthermore, the recent breakthrough in engineering colloidal quasicrystals using DNA-modified building blocks proves that programmable matter can be designed to achieve thermodynamic stability through specific geometric motifs, Zhou W., et al. (2024). These "entropy-stabilized" axial structures suggest that the CaMKII-MT complex, guided by 5,281 phosphorylation states, serves as a programmable seed for a similar phase transition within the neuronal cytoplasm.

6.3. Photonic Confinement and Field Reconstruction

A major empirical gap in holographic brain theories has been the mechanism for "launching" and "trapping" light within the dense cytoplasmic medium. Recent work on 3D-printed bio-photonic architectures shows that quasicrystal-decorated surfaces act as "photon scattering hotspots", Kumbhakar P., et al. (2023). These structures outperform traditional materials like graphene in image contrast

and optical confinement via Surface Plasmon Resonance (SPR). We propose that the quasicrystalline potential (V_{QC}) in the cytoplasm acts as a natural bio-photonic lattice, trapping the super-radiant emissions from microtubules to create the high-fidelity 3D visual "Self".

6.4. Transduction via Vibrational Coherence

The bridge between chemical signaling and physical field emission is found in molecular vibrations, Jaross W. (2020). Information exchange within the cell likely relies on the emission and resonance of electromagnetic patterns in the infrared (IR) frequency range. Coherence in these patterns is achieved through phosphorylation—specifically the 5,281 states of the "Hameroff Bytes"—which induces the necessary fingerprint patterns to activate enzymes and stabilize the field.

Appendix A Appendix - Enhanced Super-Radiant Scaling with LSPR Coupling

This appendix shifts the model from a purely "emitter" based system to an "emitter-scatterer" hybrid, where the cytoplasm acts as an active photonic lattice. The traditional N^2 scaling describes the cooperative emission of N dipoles. To account for the Enhanced Light Scattering provided by the quasicrystalline (QC) matrix, we introduce a Geometric Gain Factor (G_{QC}). This factor accounts for the Localized Surface Plasmon Resonance (LSPR) and Total Internal Reflection (TIR) within the bio-photonic architecture. The effective intensity I_{eff} of the holographic field is:

$$I_{eff}(\mathbf{r}) = G_{QC}(\mathbf{r}) \cdot \left(\sum_{i=1}^{N_{eff}} \mathbf{p}_i \right)^2$$

Where:

- $N_{eff} = N_{sub} + N_w$: The sum of active protein subunits and icosahedral water dipoles.
- $G_{QC}(\mathbf{r})$: The spatial gain function determined by the 2D/3D quasicrystalline tiling, which acts as a "photon scattering hotspot".
- $\mathbf{p}_i$: The dipole moment of the i -th element, now modulated by infrared (IR) vibrational "fingerprints".

2. The Extended Nishiyama-Jaross Lagrangian ($\mathcal{L}_{ext}$) To incorporate the Molecular Vibration and Collective Protein Behavior, the Lagrangian must include a specific term for the vibrational IR resonance triggered by the "Hameroff Byte" (phosphorylation).

$$\mathcal{L}_{ext} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{EM Field}} + \underbrace{\varphi^* \left(iD_0 + \frac{\mathbf{D}^2}{2m} \right) \varphi}_{\text{Coherent Water}} + \underbrace{\mathcal{L}_{vibe}(M(\mathbf{r}), \omega_{IR})}_{\text{Vibrational Coupling}} - \underbrace{V_{QC}(\mathbf{r})|\varphi|^2}_{\text{Photonic Potential}}$$

The new interaction term, $\mathcal{L}_{vibe}$, defines the mechanism for high-fidelity information transfer:

$$\mathcal{L}_{vibe} = \int d\omega \zeta(\omega) \left[M(\mathbf{r}) \cdot e^{-i\omega_{IR}t} \right] \otimes \Psi_{RF}$$

- $M(\mathbf{r})$: The spatial "mask" of the 5,281 phosphorylation states.
- ω_{IR} : The infrared frequency range ($10^{12} - 10^{14}$ Hz) where molecular vibrations generate coherent electromagnetic patterns.
- $\zeta(\omega)$: The coherence coefficient; radiation must be coherent to activate the enzymatic/computational processes of the cytoplasm.

3. The "Wavefront Lock" Hamiltonian ($\mathcal{H}_{lock}$) The "Wavefront Lock" is now mathematically justified as an entropy-stabilized state, similar to DNA-engineered colloidal quasicrystals. The stability is provided by the maximization of duplex-like bonding (hydrogen bonds) and facet alignment.

$$\mathcal{H}_{lock} = \int d^3x \left(\gamma_{ao} |A(\mathbf{r})|^2 S(\mathbf{r}) + \eta \nabla S \cdot \nabla \varphi \right) + \Delta S_{entropy}$$

- $\Delta S_{entropy}$: The configurational entropy that provides thermodynamic stability to the axial quasicrystalline layers.

$S(\mathbf{r})$: The acoustic scaffolding (phonons) which Mitchison identifies as the missing "integrated behavior" of the cytoplasm.

References

- 1 Craddock T., Tuszyński J. A., Hameroff S. (2012). Cytoskeletal Signaling: Is Memory Encoded in Microtubule Lattices by CaMKII Phosphorylation?
<https://doi.org/10.1371/journal.pcbi.1002421> *PLoS Computational Biology*.
- 2 Escolà-Gascón, Á. (2025). Evidence of quantum-entangled higher states of consciousness. *CSBJ*
<https://pmc.ncbi.nlm.nih.gov/articles/PMC11960655/>.
- 3 Penrose, R., & Hameroff, S. (2011). Consciousness in the universe: A review of the 'Orch OR' theory. *Physics of Life Reviews*.
- 4 Nishiyama A., Tanaka S., Tuszyński J. A. (2024a) Quantum Brain Dynamics: Optical and Acoustic Super-Radiance via a Microtubule
<https://www.mdpi.com/2673-9321/4/2/19>
- 5 Saxena K., Singh P., Sarkar J., Sahoo P., Ghosh S., Krishnananda S. D., Bandyopadhyay A. (2022) Polyatomic time crystals of the brain neuron extracted microtubule are projected like a hologram meters away
<https://pubs.aip.org/aip/jap/article-abstract/132/19/194401/2837827/Polyatomic-time-crystals-of-the-brain-neuron>
- 6 Latif W. A., Ggha S. (2019) Understanding Neurobehavioural Dynamics: A Close-Up View on Psychiatry and Quantum Mechanics
<https://pmc.ncbi.nlm.nih.gov/articles/PMC6419875/>
- 7 Greenacre L. (2025) A quantum mechanical explanation for auditory-visual hallucinations
<https://doi.org/10.1016/j.mehy.2024.111554>
- 8 So M.T-W., Ullah A., Waris A., Alhumaydhi F. A. (2025) The Etiological Role of Impaired Neurogenesis in Schizophrenia: Interactions with Inflammatory, Microbiome and Hormonal Signaling
<https://www.mdpi.com/1422-0067/26/19/9814>
- 9 Escolà-Gascón Á., Benito-León J. (2025) Mathematical proof of the Fisher-Escolà Q statistical distribution in quantum consciousness modeling
<https://pubmed.ncbi.nlm.nih.gov/40475802/>
- 10 Jennifer Rodríguez-Vázquez, Ignacio Camacho-Arroyo, Javier Velázquez-Moctezuma (2012) Differential impact of REM sleep deprivation on cytoskeletal proteins of brain regions involved in sleep regulation
<https://pubmed.ncbi.nlm.nih.gov/22456537/> doi: 10.1159/000330010. Epub 2012 Mar 27.
- 11 Jan Pokorný, Jiří Pokorný, Jan Vrba (2021) Generation of Electromagnetic Field by Microtubules
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8348406/>
- 12 Tenzin Desel, Matthew P Walker, Chelsea Brown, Cindy Chen, Trevor A Chadwick, William J Jagust, Omer Sharon (2025)
REM Sleep Misfires: Intruding Delta Waves Forecast Tau, Amyloid, and Forgetting in Aging bioRxiv [Preprint]. 2025 Aug 22:2025.08.18.670879. [Version 1] doi: 10.1101/2025.08.18.670879
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12393412/>
- 13 Ziyue Wang, Xiang Fei, Xiaotong Liu, Yanjie Wang, Yue Hu, Wanling Peng, Ying-wei Wang, Siyu Zhang, Min Xu (2022) REM sleep is associated with distinct global cortical dynamics and controlled by occipital cortex Nat Commun. 2022 Nov 12;13:6896. doi: 10.1038/s41467-022-34720-9
<https://pmc.ncbi.nlm.nih.gov/articles/PMC9653484/>
- 14 Fan Nils Yang, Dante Picchioni, Jacco A de Zwart, Peter van Gelderen, Jeff H Duyn (2025) Increased intrathalamic and thalamo-cortical functional connections during human REM sleep: Insights from a two-night EEG-fMRI study
Imaging Neurosci (Camb). 2025 Nov 20;3:IMAG.a.1026. doi: 10.1162/IMAG.a.1026
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12635483/>
- 15 Travis J A Craddock, Philip Kurian, Jordane Preto, Kamlesh Sahu, Stuart R Hameroff, Mariusz Klobukowski, Jack A Tuszyński (2017) Anesthetic Alterations of Collective Terahertz Oscillations in Tubulin Correlate with Clinical Potency: Implications for Anesthetic Action and Post-Operative Cognitive Dysfunction

- Sci Rep. 2017 Aug 29;7:9877. doi: 10.1038/s41598-017-09992-7
<https://pmc.ncbi.nlm.nih.gov/articles/PMC5575257/>
- 16 Stuart Hameroff (2022) Consciousness, Cognition and the Neuronal Cytoskeleton - A New Paradigm Needed in Neuroscience
 Front Mol Neurosci. 2022 Jun 16;15:869935. doi: 10.3389/fnmol.2022.869935. eCollection 2022.
<https://pubmed.ncbi.nlm.nih.gov/35782391/>
 - 17 Akihiro Nishiyama, Shigenori Tanaka, Jack A. Tuszynski, and Roumiana Tsenkova (2024b) Holographic Brain Theory: Super-Radiance, Memory Capacity and Control Theory
 Int. J. Mol. Sci. 2024, 25(4), 2399; <https://doi.org/10.3390/ijms25042399>
<https://www.mdpi.com/1422-0067/25/4/2399>
 - 18 Christopher R. Iacovella, Aaron S. Keys, and Sharon C. Glotzer (2011) Self-assembly of soft-matter quasicrystals and their approximants
<https://pmc.ncbi.nlm.nih.gov/articles/PMC3248498/>
 - 19 Conrad Möckel, Abin Biswas, Simone Reber, Aleksei Chechkin, Vasily Zaburdaev, Jochen Guck (2025) Hierarchical Heterogeneities in Spatio-Temporal Dynamics of the Cytoplasm
<https://www.biorxiv.org/content/10.1101/2025.05.08.652886v2.full>
 - 20 John Gardiner (2015) Subcellular neuronal quasicrystals: Implications for consciousness
 Commun Integr Biol. 2015 Mar 4;8(1):e1000700. Doi: 10.1080/19420889.2014.1000700
<https://pmc.ncbi.nlm.nih.gov/articles/PMC4594252/>
 - 21 Matija L. R., Stankovic I. M., Puric M., Miličić M., Maksimović-Ivanić D., Mijatovic S., Krajnović T., Gordic V., Koruga D. L. (2023). The Second Derivative of Fullerene C60 (SD-C60) and Biomolecular Machinery of Hydrogen Bonds: Water-Based Nanomedicine. *Micromachines*, 14(12), 2152.
<https://doi.org/10.3390/mi14122152>
 - 22 Mitchison T. J. (2017). Remaining Mysteries of the Cytoplasm. *Molecular Biology of the Cell*, 21(22).
<https://doi.org/10.1091/mbc.e10-02-0084>
 - 23 McLean R. J., Pessoney G. F. (1970). A large scale quasi-crystalline lamellar lattice in chloroplasts of the green alga *Zygnema*. *The Journal of Cell Biology*, 45(3).
<https://doi.org/10.1083/jcb.45.3.522>
 - 24 Zhou W., et al. (2024). Colloidal quasicrystals engineered with DNA. *Nature Materials*, 23, 424–428.
<https://www.nature.com/articles/s41563-023-01706-x>
 - 25 Kumbhakar P., et al. (2023). Enhanced Light Scattering Using a Two-Dimensional Quasicrystal-Decorated 3D-Printed Nature-Inspired Bio-photonics Architecture. *The Journal of Physical Chemistry C*.
<https://pubs.acs.org/doi/10.1021/acs.jpcc.3c00513>
 - 26 Jaross W. (2020). The Possible Role of Molecular Vibration in Intracellular Signaling. *Journal of Cellular Signaling*, 1(4).
<https://doi.org/10.33696/Signaling.1.027>
 - 27 Akihiro Nishiyama, Shigenori Tanaka, Jack A. Tuszynski (2024c) Quantum Brain Dynamics and Virtual Reality
<https://www.sciencedirect.com/science/article/pii/S0303264724001448>
 - 28 Deepa H. Rajan and Wallace F. Marshall (2024) Cellular cognition: How single cells learn using non-neural networks
 Department of Biochemistry and Biophysics, University of California, San Francisco
<https://doi.org/10.1016/j.cub.2024.11.016>
 - 29 Federico Pigozzi, Adam Goldstein and Michael Levin (2025) Associative conditioning in gene regulatory network models increases integrative causal emergence
<https://www.nature.com/articles/s42003-025-08411-2>
 - 30 Nhi Doan, Austen Theroux, Tejas Ramdas, Samuel J. Gershman (2026) Associative learning in the protozoan *Stentor coerules*
 Department of Psychology and Center for Brain Science, Harvard University
<https://www.biorxiv.org/content/10.64898/2026.02.25.708045v1.full.pdf>

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