

(Short Paper) Super-Intercellular Synchronization and High-Light Adaptation in 4-Cell Green Alga *Tetrabaena*: A Spatially Extended Quantum Computing Model via a 4-QPU Array

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Abstract

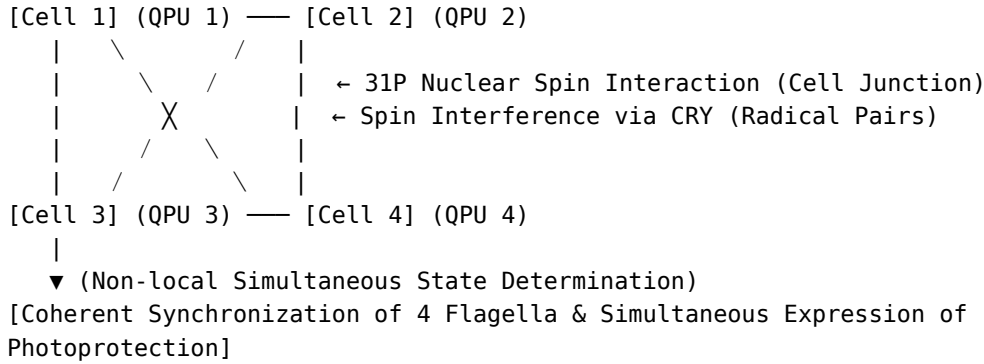
Tetrabaena socialis, a four-celled colonial green alga arranged in a planar square, exhibits hydrodynamically synchronized swimming despite each cell possessing autonomous flagella. Furthermore, unlike related species that execute phototactic avoidance migrations under intense light stress, *T. socialis* adopts a distinct survival strategy by remaining in place and synchronously activating photoprotective and antioxidant defense metabolic pathways across all cells. In this paper, we formulate the four-cell architecture of *Tetrabaena* as the minimal multi-qubit quantum array composed of four spatially coupled local QPUs. Mediated by ^{31}P nuclear spin memories in Posner molecules and quantum correlations across cellular junctions, we elucidate the physical mechanism by which the four cells function as a “single quantum system,” executing non-local in-phase synchronization and metabolic optimization independent of classical molecular diffusion or membrane potential propagation delays.

1. Introduction: The Paradox of Synchronization Delay at the Dawn of Multicellularity

Occupying an early transitional stage in the evolution from unicellular to multicellular life, *Tetrabaena* possesses the simplest multicellular organization. Although each constituent cell maintains an independent metabolic system and locomotive organelle (flagella), individual cells do not move randomly in fluid environments; instead, they generate coordinated propulsion without sub-millisecond delays.

Moreover, under excessive light stress, closely related organisms such as unicellular *Chlamydomonas* or large colonial *Volvox* execute phototactic avoidance swimming, whereas *Tetrabaena* exhibits no spatial retreat. Instead, all cells synchronously activate photoprotective compound synthesis and antioxidant stress responses while maintaining their physical location. Classical intracellular signaling reliant on fluid fluctuations or morphogen diffusion cannot account for the instantaneous capacity of four independent cells to arrive at an identical, globally optimal decision (avoidance versus defense) and synchronize their mechanical movements without spatial discrepancies.

2. Physical Mechanisms of the 4-QPU Array Model



1. Nuclear Spin Correlation at Cell Junctions (QPU Array Formation):

The central junctional boundaries where the four cells interface harbor high densities of membrane phosphate groups and clustered Posner molecules. The ^{31}P nuclear spin memory within each cell is not isolated; rather, it undergoes inter-membrane spin-spin interactions across the junction, establishing an entangled superposition state (4-qubit array) encompassing all four cells.

2. Quantum Annealing Evaluation of High-Light Adaptation (Defense Strategy Determination):

When the photoreceptor cryptochrome (CRY) detects excessive radiant energy, the generated electron-spin radical pairs trigger correlative operations across the collective 4-QPU array. The computational trade-off between the kinetic energy cost of migration/avoidance and the biological cost of in situ photoprotection is evaluated in parallel within a quantum superposition, instantaneously collapsing (projecting) into the coordinated activation of defensive metabolism.

3. Non-local In-Phase Flagellar Synchronization:

The computational output is transmitted simultaneously to the basal bodies of all four flagella via Quantum Pulse Communication (QPC). Eliminating classical delays associated with chemical reception or membrane depolarization cascades enables robust phase locking against dynamic hydrodynamic resistance, maintaining rectilinear trajectory alignment.

3. Conclusion

The high-precision locomotive synchronization and adaptive strategies observed in *Tetrabaena* demonstrate that the fundamental emergence of multicellularity is not merely a mechanical aggregation of cells, but a physical transition wherein autonomous QPUs share entangled states, scaling into a coherent multi-bit QPU array. This model provides a quantitative framework for understanding the spatial expansion of quantum coherence from LUCA to macroscopic multicellular organisms.

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