Quantum optical mega-networks in biological architectures, and the computational capacity of life

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***Abstract* – In this talk I will present an overview of our work analyzing mega-networks of tryptophan in biological architectures with numerical simulations and steady-state ultraviolet spectroscopy [1, 2], providing opportunities for measurement, readout, and control of light-matter interactions in large protein aggregates, cellular organelles, and neuronal bundles. I will then, based on these insights and fundamental physical considerations, consider the computational limits of living systems. As time permits, the implications for information processing in aneural organisms like the humble slime mold and for the development of artificial intelligence(s) will also be discussed.**

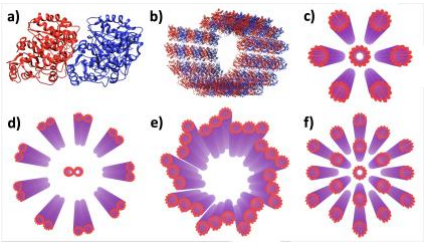

Fig. 1: Hierarchical mega-networks of quantum emitters form in protein architectures of functional biological significance, enhancing observed measurements of fluorescence quantum yield even in the presence of significant disorder [1].

Networks of tryptophan – an aromatic amino acid with strong fluorescent response – are ubiquitous in biological systems, forming diverse architectures in transmembrane proteins, cytoskeletal filaments, sub-neuronal elements, photoreceptor complexes, virion capsids, and other cellular structures. We analyze the cooperative effects induced by ultraviolet (UV) excitation of several biologically relevant tryptophan mega-networks, thus giving insight into novel mechanisms for cellular signalling and control. Our theoretical analysis in the single-excitation manifold predicts the formation of strongly superradiant states due to collective interactions among organized arrangements of up to more than 100,000 tryptophan UV-excited transition dipoles in microtubule architectures, which leads to an enhancement of the fluorescence quantum yield that is confirmed by our experiments [1]. We demonstrate the observed consequences of this superradiant behavior in the fluorescence quantum yield for hierarchically organized tubulin structures, which increases in different geometric regimes at thermal equilibrium before saturation – highlighting the effect's persistence in the presence of significant disorder. Contrary to conventional assumptions that quantum effects cannot survive in large biosystems at high temperatures, our numerical results [2] suggest that macropolymer lattices of tryptophan in microtubules, actin filaments, and amyloid fibrils exhibit increasingly observable and robust effects with increasing length, due to quantum coherent interactions in the single-photon limit. Superradiant enhancement and high quantum yield in neuroprotein polymers would thus play a crucial role in information processing in the brain, the development of neurodegenerative diseases such as Alzheimer's and related dementias, and a wide array of other pathologies characterized by anomalous protein aggregates. Our results motivate a revisiting of the computing limits of cytoskeletal and neuronal architectures, which are generally considered to signal via Hodgkin-Huxley action potentials (~millisecond) rather than via superradiant states in such tryptophan lattices (~picosecond). The latter would allow processing of orders of magnitude more information than exascale supercomputers, at significantly lower power consumptions, by operating extremely close to the Landauer bound for logically irreversible operations. The robustness of superradiant states paired with subradiant states (~second) in proteins thus offers a novel paradigm for understanding the role of large collectives of quantum emitters in warm, wet, and wiggly environments.

ACKNOWLEDGEMENTS

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REFERENCES

[1] N.S. Babcock, G.M.-Cabrera, K.E. Oberhofer, M. Chergui, G.L. Celardo, and **P. Kurian**. “Ultraviolet Superradiance from Mega-Networks of Tryptophan in Biological Architectures.” *J. Phys. Chem. B* **128**, 4035–4046 (2024). DOI: 10.1021/acs.jpcb.3c07936

[2] H. Patwa, N.S. Babcock, and **P. Kurian**. “Quantum-enhanced photoprotection in neuroprotein architectures emerges from collective light-matter interactions.” In review, *Frontiers in Physics* (2024).