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

Tuesday, 26 September 2023 14:30 (30 minutes)

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, providing opportunities for control of light-matter interactions in cellular organelles and neuronal bundles. I will then, based on these insights and fundamental physical considerations, consider the computational limits of living systems and all matter in the observable universe. The implications for development of artificial intelligence(s) will also be discussed.

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. 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. Our results motivate a revisiting of conventional assumptions about the computing limits of cytoskeletal and neuronal architectures, which are generally considered to signal via Hodgkin-Huxley action potentials (millisecond timescale). It is shown that these biosystems can harness superradiant effects (picosecond timescale) in tryptophan lattices to process 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 single-photon-excited superradiant states paired with subradiant states (second timescale) in biology thus offers a novel paradigm for understanding large collectives of quantum emitters and their quantum information processing limits in warm, wet, and wiggly environments.

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