

This essay describes the quantum biology of catalysis, metabolism, homeostasis, and cell signaling processes. It also proposes an intracellular Quantum Biology Device (QBD) to test quantum effects directly in living cells, outlining its design, experiments, and implications. The essay concludes that a full understanding of life requires a quantum sciences and technologies and developing tools like the QBD could transform both biology and medicine.

Introduction: Quantum Science is essential to life.

Physiology studies the functions and mechanisms of living systems. As a discipline, it integrates knowledge about organisms across temporal, spatial, and hierarchical biological scales. Its approach provides increasingly refined explanations of macroscopic phenomena from their molecular causes. In principle, the functions of all organisms should be explainable within the realm of physiology. To pursue this ambitious goal, physiologists use models and methods from physics to quantify and predict flows and transformations of energy and matter. The field is also rooted in chemistry, which elucidates biological structures, enzymatic reactions, and metabolism. Homeostasis is a core concept in physiology, referring to the regulation of internal variables (such as temperature, pH, and ion concentrations) that keep organisms stable despite environmental fluctuations. Another central theme is cell signaling, the set of processes by which cells communicate with themselves, with other cells, and with their surroundings. Signaling requires three elements: a signal, a receptor, and an effector. Most signals are chemical molecules that bind to and activate specific receptors, though physical cues such as pressure, voltage, and temperature can also mediate signaling. This essay argues that quantum sciences are fundamental to the existence of life, as physiology itself is rooted in quantum principles. Core physiological processes, such as enzyme catalysis, metabolism, homeostasis, and cell signaling, are mediated or enhanced by quantum phenomena including photons, excitons, spin dynamics, quantum noise, radical pairs, tunneling particles, and entangled states (Lambert et al., 2013). Building on recent research, the essay contends that the phenomena currently identified as quantum biology emerge from quantum principles embedded at the foundation of physiology. To illustrate the implications, it outlines the design of a device capable of investigating intracellular quantum phenomena in vivo and explains how such an apparatus could operate. The potential discoveries and transformative consequences of this instrument are considered alongside key counterarguments. The essay concludes by synthesizing the main insights and emphasizing the paradigm shift that quantum physiology brings to our understanding of life.

1st part of the argumentation: Quantum Physiology

Quantum physiology describes and explains how the functions and mechanisms that sustain life both rely on and are optimized by quantum phenomena. Whereas classical physiology interprets processes in terms of deterministic biochemical pathways, quantum physiology reframes them as systems that have evolved to exploit coherence, tunneling, entanglement, and spin dynamics to achieve efficiency, sensitivity, and robustness under the noisy and warm conditions of living cells. Evidence increasingly suggests that life has actively recruited quantum features into the most essential components of physiology, across all life forms on this planet. To support this argument, four core processes will be examined: enzyme catalysis, metabolism, homeostasis, and cell signaling. Enzymes accelerate chemical reactions by extraordinary factors, sometimes up to 10¹⁸ times faster than uncatalyzed rates. Classical models attribute this acceleration to lowered activation energy, but such explanations often fail to align with experimental results. Enzyme catalysis relies on proton and electron tunneling, which allow particles to cross otherwise prohibitive energy barriers (Hammes-Schiffer, 2006). Without tunneling, many reactions would proceed too slowly to sustain metabolic flux. Protein dynamics also appear evolutionarily tuned to synchronize donor and acceptor states, thereby maximizing tunneling probability. This quantum enhancement is crucial: without it, core metabolic processes would likely have been too slow for complex life to emerge, as entropy would disrupt molecular assemblies before replication could stabilize them. Enzymatic tunneling therefore underpins metabolism, enabling the chains, cycles, and processes that sustain life. This same quantum optimization is evident in metabolism. Metabolism enables organisms to grow, reproduce, maintain structures, and respond to their environment through functions that convert food into usable energy or macromolecules such as proteins, lipids, nucleic acids, and carbohydrates. Photosynthesis, the primary entry point of energy into ecosystems, relies on long-lived quantum coherence, in which excitons behave as waves and simultaneously explore multiple pathways before collapsing into the most efficient route (Panitchayangkoon et al., 2010). Femtosecond laser spectroscopy has revealed that light-harvesting complexes in plants and bacteria transfer excitonic energy to

reaction centers with near-perfect efficiency, ensuring photon capture and energy transport approach 100%. Without this quantum boost, energy conversion would be too inefficient to sustain multicellular complexity. Because photosynthesis initiates nearly all metabolism on Earth, subsequent pathways such as ATP production, carbon fixation, and biosynthesis inherit this fundamental quantum optimization. In addition, electron tunneling across redox cofactors plays a critical role in proton pumping and ATP synthesis, both of which are vital for maintaining homeostasis. Homeostasis likewise depends on the precise regulation of variables such as temperature, pH, ionic balance, and metabolite concentrations. This regulation requires both a steady energy supply, mainly from ATP, and the sensitive detection of environmental cues. A well-studied example of biological quantum sensing is avian magnetoreception, where migratory birds use the radical-pair mechanism in cryptochromes to detect Earth’s magnetic field (Hore & Mouritsen, 2016). Radical pairs exhibit spin-correlated states whose singlet-triplet dynamics can be modulated by weak magnetic fields, a sensitivity that arises directly from quantum spin coherence. Emerging evidence suggests that similar spin-dependent processes may influence cellular phenomena such as mitosis, tissue repair, and embryonic development. Cells appear capable of detecting extremely weak magnetic fields—on the order of femtotesla, a billionth of Earth’s field—generated by intracellular activity. If confirmed, this form of quantum sensing could explain ultrafast, atomic-scale communication that helps coordinate cell replication and maintain physiological stability. Finally, cell signaling illustrates how quantum optimization extends to communication networks. Cell signaling coordinates physiology across scales, from intracellular pathways to organism-wide responses. Traditionally, signaling has been described in terms of chemical ligand-receptor interactions and classical physical cues such as pressure, voltage, and temperature. Yet at smaller and faster scales, quantum mechanisms may also mediate these processes. One example is the vibrational theory of olfaction, which proposes that receptors detect molecular vibrations through inelastic electron tunneling rather than shape alone, highlighting how tunneling could underlie sensory signaling. Other cases—including gene expression, circadian rhythms, and stress responses—have been hypothesized to involve spin-dependent reactions and radical-pair dynamics. In addition, quantum coherence in excitonic transport may contribute to energy signaling between organelles, such as between chloroplasts and mitochondria in plant cells. Collectively, these examples suggest that evolution has recruited tunneling, coherence, and spin dynamics to achieve levels of sensitivity, coordination, and robustness in communication networks that would be unattainable through classical mechanisms alone. Taken together, enzyme catalysis, metabolism, homeostasis, and cell signaling point to a unifying principle: over billions of years, evolution has consistently exploited quantum effects to optimize physiology. This is not peripheral but foundational to life itself—without tunneling, metabolic rates would be sluggish; without coherence, photosynthesis would fail to generate biomass efficiently; without spin sensitivity, errors in mitosis could compromise the stability of multicellular life. This evolutionary pattern, coupled with its ubiquity across ecosystems, implies that quantum physiology offers a new conceptual and mathematical framework for understanding life’s core processes. It shows that these processes are not merely classical phenomena, but quantum-optimized systems shaped by evolution. By unifying these diverse examples, quantum physiology strengthens the claim that a complete comprehension of biology requires quantum science.

2nd part of the argumentation: the technologies and methods to uncover Quantum Physiology

It is prudent to recall Carl Sagan’s adage that “extraordinary claims require extraordinary evidence.” In this context, such evidence must consist of direct experimental confirmation of nonclassical quantum effects under physiologically relevant *in vivo* conditions. Direct, well-controlled measurements should converge with theoretical characterization of the system. To characterize a physical system is, roughly, to provide a mathematical description of its state and to predict its evolution over time. Operationally, a system’s state can be represented by a set of numbers, often arranged as a vector or a matrix with complex components, that encode all measurable properties of the system. Because quantum mechanics is probabilistic, these states determine the probability distributions of outcomes for permissible measurements performed on the system. Quantum measurements in controlled systems (that are cold, stable, and simple) are extremely precise and forms a pillar of modern science. Therefore, most evidence in quantum biology has been obtained *in vitro* or in simplified preparations, often at cryogenic temperatures, where fragile quantum states are easier to observe (Lambert et al., 2013). By contrast, demonstrating tunneling, coherence, entanglement, and spin correlations *in vivo*, within living cells and tissues where decoherence, noise, and complexity are pervasive, remains the central challenge. Quantum events occur on atomic length scales ($\sim 10^{-10}$ m) and femtosecond timescales ($\sim 10^{-15}$ s), whereas physiological processes span micrometers to meters and milliseconds to years.

Bridging this gap requires tools that can capture ultrafast dynamics with nanometer-scale precision inside living tissue. Coherence and entanglement decay rapidly under thermal noise, molecular collisions, and fluctuating fields. Moreover, quantum signatures, such as spin correlations, tunneling currents, and excitonic coherences, are orders of magnitude weaker than classical backgrounds (thermal fluctuations, autofluorescence, ionic currents). Detecting them in crowded, living cells is therefore comparable to hearing a whisper in kids’ playground. Current quantum probes (e.g., nanodiamonds with NV centers, quantum dots, and spin labels) are not consistently biocompatible; introducing them into cells can cause toxicity, aggregation, or functional interference (Aslam et al., 2017). Progress will require simultaneous measurement of photons, spins, and vibrational modes in live cells to improve the signal-to-noise ratio. Yet most available instruments (ultrafast spectrometers, confocal microscopes, magnetic-resonance platforms) remain siloed; thus, there is a need to design an integrated device that unifies these modalities while addressing the constraints noted above. An apparatus capable of discoveries at this scale is already taking shape, drawing on advances in quantum sensing, nanoscale photonics, molecular engineering, and AI-driven analysis. Like optical microscopy in the seventeenth century, such a device could underpin a new era of physiology, enabling direct interrogation of life’s quantum foundations. It would expand physiology’s explanatory reach by integrating quantum mechanics into models of enzyme catalysis, metabolism, homeostasis, and signaling. The clinical implications could be profound: quantum-targeted therapies for enzyme deficiencies, diagnostics based on spin states, and quantum-informed bioengineering for improved energy efficiency. Consequently, developing such a device would be among the great scientific endeavors of the twenty-first century. Although probing quantum phenomena directly inside living cells once seemed impossible, advances in ultrafast optics, spin physics, and nanoscale sensing have brought the concept of a Quantum Biology Device (QBD) within reach. The following sections outline a practical, plausible design that balances physical realism with forward-looking features, explain how the QBD would operate in representative experiments, and examine the potential discoveries and broader consequences of its extensive use. The envisioned Quantum Biology Device (QBD) would integrate technologies advancing rapidly (including NV-center nanoprobe, ultrafast optical systems, microfluidics, and AI-based analysis) into a single platform capable of probing quantum phenomena *in vivo*. While full integration remains aspirational, the convergence of these fields makes the QBD scientifically justified and technically plausible. The optical subsystem should include femtosecond-pulsed lasers with pulse shaping and delay lines for pump-probe experiments and two-dimensional electronic spectroscopy to probe excitonic coherence and lifetimes. It should also support selective chromophore excitation and optogenetic activation. Single-photon avalanche diodes and photomultiplier tubes would detect photons, while precision coils with microwave/RF delivery would control and read out spin states. Microfluidics will enable precise chemical delivery, exchange, and electrical measurements (e.g., action potentials, membrane voltage, local ionic currents). The setup must be protected by active Helmholtz coils to apply or null background magnetic fields, together with stabilization of temperature, gas composition, and humidity, and acoustic/vibrational isolation to preserve measurement fidelity. By integrating these components, the instrument can measure photons (optical coherences), spin signals (magnetic signatures), and tunneling/electron currents (electrical readouts) simultaneously or in coordinated sequences. The platform will generate petabyte-scale datasets, requiring analysis software capable of quantum-state tomography, correlation analysis, and machine-learning-based denoising and event detection to extract weak coherence signatures from noisy backgrounds. A representative experiment with the QBD would measure radical-pair spin dynamics in live retinal tissue using NV probes combined with ultrafast optical stimulation. The process begins with preparation of cultured cells, into which spin-sensitive chemical reporters are introduced via microfluidics to target specific proteins. Once the sample is mounted in an environmental stage with controlled temperature and perfusion, the system is calibrated and aligned: the imaging head is focused, and baseline NV resonance, magnetic compensation fields, and pump-probe alignment are verified. The operator then selects an acquisition protocol through the user interface and specifies key parameters: excitation wavelength, pulse timing, microwave frequency and amplitude, acquisition duration, and gating. Acquisition proceeds in synchronized sequences: optical excitation generates radical pairs, microwave pulses probe spin states, and ultrafast pump-probe pulses capture transient coherences. The QBD simultaneously collects multimodal data streams, including fluorescence lifetime maps, transient-absorption spectra, NV spin-resonance readouts, and electrophysiological signals. During acquisition, on-the-fly demodulation, correlation analysis, and machine-learning denoising provide near-real-time visualizations of spin coherence, exciton lifetimes, and tunneling events. Operators can adjust parameters such as microwave pulse timing or external magnetic fields to refine measurements. After data

collection, advanced pipelines reconstruct quantum states, fit coherence lifetimes, and perform statistical comparisons across intracellular regions, generating datasets suitable for modeling and simulation. The development of a quantum-biology device represents far more than an incremental advance in instrumentation. Its extensive use would trigger a cascade of transformative consequences across technology, the life sciences, and medicine. Because the QBD can probe quantum phenomena in progressively more complex biological samples, its application would reshape our understanding of life from the simplest purified systems to human clinical material. At the *in vitro* level, studies with isolated proteins, pigment-protein complexes, or liposomes would provide high-signal-to-noise measurements for device calibration and rigorous testing of hypotheses about tunneling, spin chemistry, and excitonic coherence. These early results would build confidence in quantum-physiological principles and establish standardized benchmarks. The QBD would also permit systematic exploration of spin-dependent reactions in controlled yet biologically relevant environments, clarifying whether specific assemblies are optimized to harness quantum effects. Applied to single cultured cells, the QBD would cross into living, dynamic physiology, enabling direct characterization of intracellular tunneling, radical-pair lifetimes, and spin-sensitive signaling. Such measurements could establish causal links between quantum processes and cellular function, with far-reaching implications for cell biology and pharmacology. At the level of organelles and tissue slices, the QBD could interrogate chloroplasts, mitochondria, and molecular machines, revealing how quantum effects scale from individual proteins to organelle networks and tissue-level architecture. These applications would likely advance understanding of photosynthesis, oxidative phosphorylation, and sensory transduction. Progressing further, measurements in small organisms and embryos would illuminate how quantum phenomena shape development, behavior, and whole-organism responses, bridging biophysical mechanisms and evolutionary fitness. Finally, extending QBD analysis to *ex vivo* biopsies and organoids would mark the entry of quantum physiology into translational and clinical medicine, offering unprecedented diagnostic sensitivity for metabolic diseases, neurodegenerative disorders, and cancer, all of which involve enzymatic and signaling dysfunctions that may be quantum in origin. The consequences of deploying the QBD across this continuum are profound. It would resolve long-standing debates by identifying which physiological processes are truly quantum-dependent and how evolution has harnessed them. In applied contexts, it would enable new diagnostics and therapeutics rooted in the modulation of tunneling pathways, spin dynamics, and coherence lifetimes. By systematically bridging scales, the QBD would become a paradigm-shifting platform that redefines physiology as a quantum-informed science and medicine as a practice grounded in life’s quantum nature.

Counterarguments: a skeptical and practical view

A common counterargument holds that, although quantum mechanics underlies chemistry, it is unnecessary and

This skepticism has merit, but key observations resist purely classical accounts: large hydrogen-isotope effects in enzyme catalysis, reports of long-lived electronic coherence in light-harvesting complexes, and spin-dependent radical-pair mechanisms in magnetoreception. Where classical models miss measured rates or efficiencies, quantum models succeed. Crucially, quantum physiology does not replace classical biochemistry; it extends it, revealing optimizations that evolution has harnessed. Claiming completeness without quantum mechanics leaves explanatory gaps. A second counterargument is practical: *in vivo* quantum states decohere rapidly, signals are faint against biological noise, and integrating ultrafast lasers, NV-center probes, and microfluidics into a biocompatible platform may be infeasible in the near term; resources, critics argue, are better spent on established tools such as single-cell sequencing or advanced imaging. The challenge is real, yet history argues for ambition: X-rays, MRI, and cryogenic electron microscopy were once dismissed and are now indispensable. The proposed Quantum Biology Device (QBD) is the next logical integration of quantum sensing, nanotechnology, and AI to probe a new dimension of biology. Even incremental steps will yield valuable spin-offs for diagnostics, materials science, and quantum computing. Though full *in vivo* characterization may take time, the pursuit itself catalyzes interdisciplinary innovation. Given the prospective scientific and clinical impact, the effort is justified despite the hurdles.

Conclusion:

This essay argues that physiology, though long explained through classical chemistry and physics, cannot be fully understood without quantum mechanics. Life’s essential processes—enzyme catalysis, metabolism, homeostasis, and cell signaling—rely on tunneling, coherence, entanglement, and spin dynamics, not as cu-

riosity but as optimizations that evolution harnessed in warm, noisy cells. The essay also addresses the technical challenge of observing these effects in vivo and outlines a prospective Quantum Biology Device (QBD) that integrates ultrafast optics, NV-center probes, microfluidics, and AI to directly measure quantum processes in living tissues, transforming physiology into a quantum-informed science. The central issue is not whether quantum mechanics underlies chemistry, but whether biological systems actively exploit nontrivial quantum effects—the evidence indicates they do. Building the tools to measure them is difficult, yet history shows such challenges can be met. Humanity should pursue the QBD boldly; doing so will answer long-standing scientific questions and unlock practical advances in diagnostics, therapeutics, and biotechnology. By confronting the quantum foundations of life, we move closer to a complete description of biology and to answering, “What is life?” This, in turn, allows us to ask the next question: “Why is there life?”