

Life emerged from molecular chaos in about 300 million years, solving a combinatorial problem that defies classical biochemistry. The **quantum-cradle hypothesis** (QCH) contends that life began on abundant minerals whose nanopores created protected niches that enabled brief, local quantum searches for thermodynamically favourable molecular configurations. This aligns with the **evolutionary quantum principle**: biology will exploit quantum phenomena whenever these confer clear and immediate benefits. The QCH extends confirmed quantum biology to life's origin, where quantum was not merely beneficial but essential.

Quantum signatures

Before we can look for quantum effects that provide biological systems with selective advantages, we must be clear on what signals from quantum physics we expect. Such **quantum signatures** are crucial in establishing clear guidelines on what may or may not have a quantum origin.

Ultrafast processes

Without isolation, quantum effects are constrained to atomic scales up to a few nanometres and nanoseconds. Reactions that depend on diffusion or condensation are much slower, usually on the scale of milliseconds or more, incompatible with quantum phenomena.

Near-unity efficiency

In warm and wet environments, such as in the crowded interior of cells, thermal noise dominates any quantum effect. We can think of thermal noise as a slowly swinging cannonball that can wreck any delicate relationship (i.e. coherence) that links quantum states of particles, atoms, or molecules. When coherence is maintained long enough, it can synchronize the evolution of quantum states, enabling superposition and interference to steer energy or charge transfer along optimal paths. Such quantum-guided transport can, in principle, drive reaction efficiencies towards unity.

Reaction rates or yields that exceed what classical thermodynamics predicts can be a sign of quantum effects, too. Quantum tunnelling allows a particle to cross an energy barrier even if it does not have the requisite kinetic energy to leap over it. The probability of success drops exponentially with the mass of the particle that tunnels through the barrier, so that only electrons, protons, and hydride ions can realistically tunnel.

Temperature-invariant performance

If a biological process occurs with similar efficiency or fidelity across vastly different ambient temperatures, it suggests that diffusive transport, which is temperature-dependent, is not a rate limiter, and that the process may rely on non-thermal mechanisms, such as quantum tunnelling or coherent energy transfer. Note that biological systems often buffer temperature effects through evolved robustness and redundancy, so that temperature invariance alone is insufficient to establish a quantum origin for the process.

Isotope-dependent performance

Isotopes are atoms that differ only in the number of neutrons. They are chemically similar as they have the same electronic structures. Any biological process that responds differently to different isotopes may be a candidate for an underlying quantum effect. A so-called kinetic isotope effect is a sign of quantum tunnelling, in which a heavier isotope's probability is suppressed by more than what can be expected classically. That said, heavier isotopes do react more slowly, so caution is advised when the effect is not as pronounced.

Another possibility for isotope-dependent performance in biological processes is nuclear or electron spin (i.e. quantized angular momentum). Isotopes have different spins and can therefore interact differently with external magnetic fields.

Sensitivity to perturbations

Processes that are sensitive to the tiniest perturbations suggest that exquisitely sensitive quantum dynamics underlie the sensing. Nature builds resilience into life forms, as that improves their survival, yet, as articulated

by the evolutionary quantum principle, may choose to solve a problem differently when there are evolutionary advantages.

What to rule out

Quantum effects that require exceptional conditions, such as a vacuum, cryogenic temperatures, persistent magnetic fields, extreme gravity, or engineered materials are not relevant to biology on Earth. Macroscopic phenomena that involve large collections of cells or entire organisms can be ruled out as candidates for quantum effects, too. The same applies to processes that require quantum coherence for a second or longer.

Exotic quantum effects such as vacuum fluctuations and their consequences appear as noise *below* the thermal noise floor and are thus irrelevant. Finally, all biological systems operate on physically low energy scales, so that relativistic (quantum) effects are irrelevant, too.

The quantum-selectivity ladder

The evolutionary quantum principle leads to the insight that biology can be classical or quantum, either by accident or because it offers genuine selective advantages. We can therefore divide all biological processes by nature’s selectivity of quantum phenomena (essential, enhanced, incidental, or irrelevant) based on three criteria:

- Is quantum required to explain a biological function?
- Is the biological function achievable by classical means?
- Is evolutionary selection evident?

	<i>Quantum required?</i>	<i>Classically achievable?</i>	<i>Selection evident?</i>
Essential	Yes	No	Yes
Enhanced	Yes	Yes	Yes
Incidental	Yes	Yes	No
Irrelevant	No	Yes	—

Non-quantum processes have proved sufficient in many instances in biology, so we must reserve quantum explanations for the few intriguing cases that demand them. Where classical models rely on highly specific parameter choices or unsupported structural assumptions, a quantum origin may merit investigation. This balanced perspective prevents us from seeing quantum mirages everywhere and instead focuses our attention on genuine quantum-biological phenomena.

With these criteria, we can assess any biological phenomenon based on whether quantum mechanics is needed to explain it. Let’s now review biological processes powered by quantum mechanics based on the quantum-selectivity ladder. Afterwards, we shall speculate on the role of quantum in the origin of life (abiogenesis), particularly its necessity and utility.

Quantum-essential processes

Mitochondria

Mitochondria produce most of our cellular energy through the electron transport chain, which relies on electron tunnelling. Mitochondrial dysfunction and oxidative damage in neurons are tied to neurodegenerative diseases, which raises the possibility that quantum effects are not only integral to healthy mitochondrial function but may also play a role in their breakdown.

Avian magnetoreception

Avian magnetoreception relies on the radical-pair mechanism: light-activated cryptochrome proteins in the birds' eyes form entangled radical pairs whose spin states are influenced by magnetic fields. The entanglement lasts approximately 100 microseconds at physiological temperatures, which is an astonishing feat of evolutionary engineering. Migratory birds have a light-dependent compass, which malfunctions in the presence of weak magnetic fields besides Earth's. Their sense of orientation remains intact when birds can still navigate by starlight, though. In complete darkness, their natural migratory sense is disrupted, which shows that light is indeed critical to birds' orientation. It also illustrates that birds rely on multiple cues to navigate. Nature favours a fallback to increase resilience.

Vision

Another process that demands quantum effects is vision. In photoreceptor cells, chromophores absorb individual photons, initiating a cascade of biochemical reactions that culminates in a neural signal. The ability to absorb specific wavelengths arises from the discrete energy levels of these protein-embedded molecules, a distinctly quantum phenomenon.

Quantum-enhanced processes

Photosynthesis

More than 95% of photons absorbed by a photosynthetic cell are converted into chemical energy. Quantum beats have been observed with ultrafast electronic spectroscopy, which classical models cannot explain; a classical energy transfer produces smooth, diffusive signals. Quantum beats arise when energy is transferred in a wavelike fashion: superpositions (i.e. linear combinations) of excited states interfere, producing oscillating signals. Some quantum effects last nearly as long in living cells as they do at cryogenic temperatures; nature can preserve coherence even in warm, noisy environments. Note that photosynthesis could operate through classical biochemistry, but not with the same efficiency.

Olfaction

Fruit flies can discriminate isotopes from their smell. The classical lock-and-key mechanism in which receptors detect molecules based on their shape and functional group cannot explain this result, as isotopes are chemically and geometrically identical. A possible explanation is inelastic electron tunnelling: an electron tunnels from a donor to an acceptor site in the olfactory receptor only if the energy lost during tunnelling matches a vibrational mode of the bound molecule. This acts as a fingerprint scanner for molecules based on their vibrational spectrum, which allows isotopes to be distinguished.

Quantum-incidental processes

Enzymes

Enzymes are biological catalysts; they accelerate biochemical reactions by lowering the activation energy required to convert reactants into products. Quantum tunnelling provides an energetically even more favourable alternative: enzymes can form or break molecular bonds by bypassing the activation barrier entirely. Note that enzymes have generally not evolved for tunnelling. When it occurs, it tends to be a by-product of geometry.

A notable exception is soybean lipoxygenase, which supports proton tunnelling. Mutations that alter its geometry change the reaction rate and kinetic isotope effect in a way consistent with tunnelling being the dominant catalytic path rather than an incidental one.

Proton transfer across the hydrogen bonds of DNA has been thought to lead to mutations in certain base pairs. When a proton tunnels prior to replication, enzymes can potentially stabilize said mutations, so that these tautomeric forms survive the replication process and introduce errors. Mutations that alter proton tunnelling distances may in turn affect enzyme efficiency and contribute to disease. While there is no direct

evidence linking genetic mutations to impaired quantum tunnelling in enzymes, researchers have only recently discovered the role of proton transfer in DNA mutation mechanisms.

Quantum-irrelevant processes

Most biochemical processes, including diseases, are adequately described by classical means. An intriguing exception, yet still speculative, is viral cell invasion. While HIV enters host cells via well-understood classical mechanisms, SARS-CoV-2, which is responsible for Covid-19, may exploit quantum tunnelling to bind its spike protein to the host cell's receptor. This interaction could involve electron tunnelling facilitated by molecular vibrations. There is no empirical confirmation of this mechanism to date. If verified, it is a quantum-incidental process, unless clear signs of adaptive optimization (e.g. enhanced binding efficiency) were also present, in which case it would be quantum-enhanced.

The quantum-cradle hypothesis

The ultimate case for quantum biology may be the origin of life itself. The earliest traces of life forms date back to 4.1 billion years ago, which is 300 million years after the crust and oceans formed. That is roughly at the same time as the peak of the Late Heavy Bombardment (LHB), which is estimated to have occurred between 4.2 and 3.4 billion years ago, during which massive asteroids repeatedly hit our planet. Life on the surface or near it, if any existed, would have been obliterated during that time, though computer simulations show that hydrothermal vents may have provided a refuge.

The origin of life presents two fundamental hurdles: the synthesis of molecular parts and the arrangement of those parts into a self-replicating pattern. While prebiotic chemistry offers plausible pathways for the former, the latter presents a combinatorial problem that is hard to solve without quantum phenomena that provide significant speed-ups within the 300 million years for the earliest life to emerge on the planet.

The **quantum-cradle hypothesis** posits that Earth's primordial environment did not just host a biochemical lottery, but that it provided the hardware for an opportunistic local quantum search that aimed to minimize energy and internal entropy.

How to make RNA

While the structure of the original single-celled organisms would have included a lipid membrane with proteins and RNA, we shall focus on RNA, because it is complex enough to be worthwhile analysing and it is self-replicating, which is a prerequisite for life. Note that what follows does not depend on RNA as the precursor to all life. It is merely used to illustrate the incredible scale of the combinatorial problem.

Spontaneous assembly While the smallest prebiotic RNA replicator is 20 nucleotides long, any basic life form must have had at least 100 units. Even with trillions of parallel reactions occurring every millisecond for hundreds of millions of years across the entire planet, a classical search could not plausibly explore a space of this magnitude, as shown in the technical notes.

A quantum search could, in principle, reduce the search complexity from an astronomically improbable N combinations to a slightly more tractable $\sqrt{N}$, but it would require quantum coherence at a stage of evolution when no shielding, as in avian magnetoreception, is likely to have existed. Nature must therefore have acted more opportunistically.

If the energy gap between a short stable, folded polymer and an unstable one is on the order of a hydrogen bond (0.1 eV), Heisenberg's uncertainty relations give a characteristic quantum evolution timescale of about 3.3 femtoseconds. In warm watery environments, decoherence tends to occur on femtosecond-to-picosecond scales, which might permit only very short quantum searches, far too brief for the full combinatorial space of RNA assembly to be explored coherently. And that leads us to the idea of gradual assembly.

The assembly ratchet What if instead longer RNA chains were pieced together in a ratchet-like fashion?

1. Short polymer fragments (e.g. trimers, tetramers) form, which relax into their optimal conformation almost instantaneously.
2. The stable fragments link up in a classical manner through a condensation reaction (i.e. ligation).
3. Within a protected niche, the combined fragment performs an ultrafast local quantum search of all possible configurations, relaxing into the most stable one. Because each fragment already starts in an energetically favourable fold, the search space after ligation is relatively small.
4. Rinse and repeat.

What would such a protected niche look like? Nanometre-scale pores in minerals such as zeolites, layered silicates, or clays are prime candidates, because they were abundant on Earth billions of years ago and they support wet/dry cycles to flush reactants in and out (hence “rinse and repeat”), enabling stepwise assembly. The building blocks of RNA can indeed form in aqueous micro-droplets.

Within these pores, confinement restricts the motion of water, filtering out many low-frequency collective vibrations (i.e. phonons) that couple to molecular conformations. Hydration layers form in ordered ice-like arrangements near hydrophilic surfaces inside the pore, which limits dielectric noise. Together, these effects could reduce decoherence rates to make a brief quantum search feasible.

No rare, perfect crystals are needed; any defect or cavity that yields a few nanometres of confinement can provide partial shielding for up to a few dozen nucleotides. The regular geometry of crystal lattices can orient reactants for efficient ligation, aided further by catalytic surface sites in many clays and zeolites. Such niches may have acted as the quantum cradle of life.

The problem is now twofold: first, create a good short polymer. Second, filter the viable polymers from a pool of short molecules and gradually assemble the RNA chain in a ratchet-like manner. As shown in the technical notes, this becomes feasible in the time frame for life to emerge on the planet, though it remains a formidable challenge for purely classical approaches.

Even if we solve the combinatorial problem of the first RNA replicator, we must not forget the subsequent challenge. Life leapt from this single molecule to a complex cell. This increase in complexity suggests that the starting point, the first replicator, was not the product of a slow, arduous, nearly miraculous fluke. It suggests the origin itself must have been rapid and efficient, producing a robust system capable of immediate and powerful evolution.

Predictions of the QCH

What *falsifiable* predictions does the QCH make?

Decoherence in protected niches

If the decoherence time inside the pore is not measurably extended beyond a few femtoseconds, the core premise of the protected niche, or quantum cradle, is falsified. This can be done with two-dimensional infrared spectroscopy (2D-IR) that compares the vibrational dephasing inside nanopores with the rest of the mineral.

Substrate tests

Lab experiments should reveal a discontinuous step in the efficiency of creating functional polymers when comparing amorphous and highly crystalline substrates. The degree of order in the crystal should be correlated with the success of the quantum search and any kinetic isotope effect. Most experiments to date have compared clay versus no clay as substrates for polymerization, not the level of crystallization.

Temperature-controlled reactors with automated wet/dry cycles, high-performance liquid chromatography to separate the polymers by length, and mass spectrometry to identify them are well within current laboratory capabilities. A final functional screen is also a standard molecular biology technique.

Geochemical screen

The oldest geological sites containing evidence of life must be re-examined not just for organic chemistry, but for the specific mineralogy and large-scale crystalline order required to act as a protected niche. Performing a suite of analyses on pristine 4-billion-year-old rocks with verified organic matter from that era is at the cutting edge of analytical geology.

Each test would have to be non-destructive to the microscopic carbon fragments inside such a perfect time capsule. Quartz might be a sensible candidate, as it is chemically inert and very durable. It would have to be checked for integrity with Raman spectroscopy, so that the composition of gas bubbles inside is consistent with the atmosphere on Earth billions of years ago. If not, the sample must be discarded as it is irrelevant.

Isotopic signatures

If proton tunnelling played a role in protected niches, we would expect to see a depleted deuterium/hydrogen ratio compared to the surrounding trapped water that is beyond the fractionation expected from classical metabolic processes. Such an anomalous isotopic ratio must appear only in carbon found on an ordered crystalline substrate that also shows evidence of wet/dry cycles.

Self-replication in open dynamical systems

So far, we have argued that certain minerals may have provided the hardware needed to perform a quantum search for life. But what could have guided such a search?

Living organisms are thermodynamic, open systems that exchange energy and matter with their environment. The constant flow of energy allows life to maintain low-entropy (ordered) states internally while increasing entropy externally. Far from equilibrium, open systems are known to spontaneously form ordered, dynamic patterns. Life clearly operates in non-equilibrium conditions, which allows it to self-organize and evolve without the guiding hand of natural selection but based on the self-organizing principles of complex dynamical systems at the edge of chaos. When taken to its logical conclusion, this idea posits that evolution is primarily a means to achieving more efficient dissipation of energy.

Note that self-replication also appears in inanimate matter, such as vortices in turbulent fluids, which illustrates that it is not unique to biology. The consequence of any future validation of a thermodynamic origin of evolution is that life is perhaps inevitable in a universe that minimizes energy while maximizing entropy, though the specifics depend on the environmental circumstances.

Conclusion

The quantum-cradle hypothesis proposes that life's first informational molecule was not found by a random search, but by a quantum exploration of thermodynamics in non-equilibrium conditions, made possible by the unique properties of common geological structures. Such a quantum cradle was not a perfectly tuned crystal that interacted in just the right way, but a passive, scrappy rock found in any coastal region, so that life could emerge in numerous places on the planet.

It relies on established chemistry (i.e. minerals catalyse RNA polymerization, wet/dry cycles enable the ratchet-like assembly of short polymers) and geology (i.e. early life existed on mineral surfaces). What it adds is that quantum physics can solve the combinatorial problem much more efficiently than classical biochemistry, or rather: abiogenesis is perhaps the best candidate for a quantum-essential process.

Confinement in natural pores creates quantum cradles that could extend coherence ever so slightly, which can bias ultrafast local reaction pathways without invoking circuit-level quantum computation, which is indeed infeasible. The quantum-cradle hypothesis is not a dismissal of classical abiogenesis, but an exploration of whether quantum effects could have tipped the scales in a needle-in-a-haystack problem.

Alternatives such as classical templating and autocatalysis cannot overcome the combinatorial barrier, whereas dissipation-driven adaptation offers a biased search but it offers no mechanism to escape energy-landscape traps, for which quantum tunnelling might be a suitable, if not the only sensible, solution.

The evolutionary quantum principle guided our quest for experimentally verified examples of quantum biology and their quantum signatures, providing the seeds for the idea that prebiotic minerals may have acted as quantum search engines for life. The quantum-cradle hypothesis transforms the origin of life from an inscrutable miracle into a question of physics applied to biology.