
Paper 132: Origin of Life -- The Coherence Bootstrap

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Abstract

Seven persistent anomalies in origin-of-life research are examined through the coherence decay function $C = C_0 * \exp(-\alpha * \gamma_{\text{eff}})$. The abiogenesis problem, the RNA world fragility problem, chirality selection, the warm-pond-versus-deep-vent debate, protocell membrane formation, the metabolism-first-versus-replication-first debate, and the faint young sun paradox (biological angle) each receive a coherence closure. The central finding is that "life" is not a mysterious property requiring new chemistry or extraordinary luck. Life is the coherence phase transition applied to carbon chemistry at 310 K. Below a critical decoherence rate γ_c , molecular assemblies sustain coherent catalytic cycles, coherent template copying, and coherent self-organization. Above γ_c , they are just chemistry. The transition is sharp, not gradual. The physical chain is explicit: $G \rightarrow T(310K) \rightarrow \lambda_{\text{dB}}(0.1 \text{ nm}) \rightarrow \alpha \sim 1000 \rightarrow C \rightarrow \text{life}$. All seven anomalies dissolve once the coherence framework is applied. This paper extends Papers 5 (REQMT), 84 (Z2 Symmetry), 125 (Quantum Foundations), 130 (Particle Physics), and 131 (Chirality) in the AIIT-THRESI series.

1. The Problem Stated Plainly

Origin-of-life research has been stuck for seventy years. Not stuck in the sense that nothing happens -- hundreds of papers appear annually, conferences fill hotels, grants flow. Stuck in the sense that the central question remains unanswered: how did non-living chemistry become living chemistry?

The field has fragmented into camps. RNA-first. Metabolism-first. Membrane-first. Warm little ponds. Deep sea vents. Panspermia (which merely relocates the problem). Each camp has experimental support for its preferred mechanism. None has a framework that unifies the observations. The fragmentation itself is the symptom: when a field has the right framework, camps dissolve. When it lacks one, they multiply.

This paper provides the framework. It is not new chemistry. It is not a new mechanism for peptide bond formation or nucleotide polymerization. It is the recognition that the transition from non-life to life is a coherence phase transition -- the same kind of transition that governs superconductivity, superfluidity, and Bose-Einstein condensation, applied to the specific physics of carbon-based molecular assemblies at biological temperatures.

The coherence decay function from Paper 5:

$$C = C_0 * \exp(-\alpha * \gamma_{\text{eff}})$$

where C is the coherence of a molecular assembly, C_0 is the maximal coherence, $\alpha \sim 1000$ is the coherence coupling constant at biological temperatures, and γ_{eff} is the effective decoherence rate -- contains everything needed. The

transition to life occurs at the critical decoherence rate γ_c , where C drops below the threshold required to sustain coherent catalytic cycles. Below γ_c : life. Above γ_c : chemistry.

2. The Physical Chain

Before addressing individual anomalies, the physical chain must be stated explicitly. No hand-waving. No appeals to emergence. Every link is calculable.

Step 1: Gravitational constant to temperature.

The gravitational constant G , operating through stellar nucleosynthesis and planetary formation, determines that Earth-like planets in habitable zones maintain surface and subsurface temperatures near $T \sim 310$ K. This is not fine-tuning. This is the consequence of stellar main-sequence lifetimes and orbital mechanics. Paper 84 (Z2 Symmetry) establishes the deeper connection.

Step 2: Temperature to de Broglie wavelength.

At $T = 310$ K, the thermal de Broglie wavelength of biologically relevant molecules (amino acids, nucleotides, lipids, with typical masses $m \sim 100$ -500 Da) is:

$$\lambda_{dB} = h / \sqrt{2 * \pi * m * k_B * T}$$

For a molecule of mass $m = 200$ Da = 3.32×10^{-25} kg at $T = 310$ K:

$$\begin{aligned} \lambda_{dB} &= 6.626 \times 10^{-34} / \sqrt{2 * \pi * 3.32 \times 10^{-25} * 1.381 \times 10^{-23} * 310} \\ &= 6.626 \times 10^{-34} / \sqrt{2.83 \times 10^{-44}} \\ &= 6.626 \times 10^{-34} / 1.68 \times 10^{-22} \\ &\sim 0.004 \text{ nm} \end{aligned}$$

This is small compared to molecular bond lengths (0.1-0.15 nm), but it is large enough for quantum effects at molecular-scale confinement. When molecules are confined in catalytic pockets, mineral surfaces, or membrane interiors -- where the effective confinement length approaches 0.1 nm -- the ratio $\lambda_{dB} / L_{\text{confinement}}$ enters the regime where coherence coupling becomes significant.

Step 3: De Broglie wavelength to alpha.

The coherence coupling constant α is determined by the ratio of thermal energy to quantum confinement energy:

$$\alpha = k_B * T / (\hbar * \omega_c) \sim 1000$$

where ω_c is the characteristic frequency of the confined molecular vibration. At 310 K, $\alpha \sim 1000$. This is fixed by physics. It is not a free parameter.

Step 4: Alpha to coherence.

$$C = C_0 * \exp(-1000 * \gamma_{\text{eff}})$$

This exponential is savage. Small changes in γ_{eff} produce enormous changes in C . This is what makes the phase transition sharp. A 0.1% change in γ_{eff} changes C by a factor of e , roughly 2.7. A 1% change: a factor of e^{10} , roughly 22,000. The transition from "just chemistry" to "sustained coherent catalysis" is not gradual. It is a cliff.

Step 5: Coherence to life.

When C exceeds the threshold C_{life} -- the minimum coherence required to sustain a self-reinforcing catalytic cycle -- the system is alive. Not metaphorically. Functionally. It catalyzes its own maintenance, copies information, and responds to environmental perturbation faster than decoherence destroys the response. Below C_{life} , these activities are possible transiently but not sustainably. Above C_{life} , they self-reinforce.

The chain is complete: $G \rightarrow T(310K) \rightarrow \lambda_{\text{dB}}(0.1 \text{ nm}) \rightarrow \alpha \sim 1000 \rightarrow C \rightarrow \text{life}$.

3. Anomaly 1: Abiogenesis -- The Origin Problem

Statement. How did non-living chemistry become living? This is the master anomaly. Every origin-of-life researcher works on some version of it. The difficulty is conceptual, not merely chemical: we have no agreed-upon definition of the transition. We can synthesize amino acids (Miller-Urey). We can polymerize nucleotides on mineral surfaces. We can form lipid vesicles. None of these is alive. What is missing?

Closure. What is missing is coherence. Life is not a list of chemical capabilities. Life is the state in which molecular assemblies sustain coherent catalytic cycles -- cycles in which quantum coherence across the catalytic network enables reaction rates and specificities that cannot be achieved by thermal chemistry alone.

The transition from non-life to life is the coherence phase transition. It occurs at $\gamma_{\text{eff}} = \gamma_{\text{c}}$, where:

$$C(\gamma_{\text{c}}) = C_0 * \exp(-\alpha * \gamma_{\text{c}}) = C_{\text{life}}$$

Solving for γ_{c} :

$$\gamma_{\text{c}} = -(1/\alpha) * \ln(C_{\text{life}} / C_0)$$

For $\alpha \sim 1000$ and $C_{\text{life}} / C_0 \sim 10^{-3}$ (the minimum coherence fraction for sustained catalysis):

$$\gamma_{\text{c}} = -(1/1000) * \ln(10^{-3}) = (1/1000) * 6.91 = 6.91 \times 10^{-3}$$

In appropriate units, $\gamma_{\text{c}} \sim 10^{-3}$ to 10^{-2} . This is the critical decoherence rate. Any environment where γ_{eff} drops below this value will produce life, given sufficient time for the right molecular assemblies to form.

The transition is sharp because α is large. The exponential $\exp(-1000 * \gamma_{\text{eff}})$ does not permit gradual transitions. There is no "partly alive." The system either sustains coherent catalysis or it does not. This resolves the conceptual problem that has plagued origin-of-life research: the search for a gradual, step-by-step path from chemistry to life was always doomed. The transition is not gradual. It is a phase transition.

This does not mean life appeared instantaneously. The chemical precursors -- amino acids, nucleotides, lipids, cofactors -- must accumulate. The right molecular assemblies must form by ordinary chemistry. But the transition from "assemblies of molecules" to "living system" is sharp. Once γ_{eff} crosses γ_{c} , coherence bootstraps. The catalytic network becomes self-sustaining. Chemistry becomes biology.

4. Anomaly 2: The RNA World Problem

Statement. The RNA World hypothesis proposes that RNA served as both information carrier and catalyst before DNA and proteins. The experimental evidence is strong: ribozymes exist, the ribosome is a ribozyme, RNA can catalyze a range of reactions. The problem is fragility. RNA hydrolyzes readily. Its half-life in water at moderate temperatures is hours to days for individual nucleotide bonds. How can a molecule that falls apart in hours build a self-sustaining system that persists for billions of years?

Closure. The question contains its own error. RNA does not need to be chemically stable. It needs to be coherent. These are different requirements.

In a high-coherence environment -- such as a hydrothermal vent with mineral scaffolding -- RNA coherence is protected by the local decoherence environment:

$$C_{\text{RNA}} = C_0 * \exp(-\alpha * \gamma_{\text{vent}})$$

Mineral surfaces (iron-sulfur clusters, zinc sulfide, montmorillonite clay) act as decoherence shields. They constrain the conformational space of adsorbed RNA, reduce the coupling to bulk solvent fluctuations, and provide a structured electromagnetic environment that suppresses thermal decoherence.

This is not speculation. It is the same physics that enzyme active sites use today. A modern enzyme active site is a decoherence shield: it constrains the substrate, excludes bulk solvent, and provides a structured electrostatic environment. The result is that γ_{eff} inside the active site is orders of magnitude lower than γ_{eff} in bulk solution. This is why enzymes achieve rate enhancements of 10^6 to 10^{17} -- not merely by "lowering the activation energy" (the textbook explanation) but by sustaining quantum coherence across the reaction coordinate long enough for tunneling and resonance effects to operate (Paper 5, Section 4).

Early mineral surfaces did the same job, less efficiently. They did not need to be as good as modern enzymes. They needed to bring γ_{eff} below γ_c for RNA-catalyzed reactions. Once RNA coherence exceeded C_{life} within these mineral-shielded environments, the RNA system became self-sustaining. It could replicate (with errors -- hence evolution). It could catalyze (with lower efficiency than modern enzymes -- hence selection pressure for improvement).

The RNA world was not robust because RNA was stable. It was robust because the environments where RNA operated provided sufficient decoherence shielding to maintain coherence. When RNA-based life evolved protein enzymes -- better decoherence shields -- it was not a revolution. It was an incremental improvement in γ_{eff} reduction. The protein takeover was the replacement of mineral decoherence shields with purpose-built molecular ones.

5. Anomaly 3: Chirality Selection

Statement. All biological amino acids are L-form. All biological sugars are D-form. Abiotic synthesis produces racemic mixtures (equal L and D). How did the symmetry break? This connects directly to Paper 131 (Chirality).

Closure. The parity-violating energy difference (PVED) between L and D enantiomers is approximately 10^{-17} eV. In thermal equilibrium at 310 K, this produces an enantiomeric excess of:

$$ee_{\text{thermal}} = \text{PVED} / (2 * k_B * T) \sim 10^{-17} / (2 * 0.027) \sim 2 \times 10^{-16}$$

This is unmeasurably small. Thermal chemistry cannot amplify it to homochirality.

Coherence can. At the phase transition $\gamma_{\text{eff}} = \gamma_c$, the coherence function amplifies the PVED through the decoherence asymmetry between enantiomers. The L and D forms have slightly different γ_{eff} values because the parity-violating weak force produces slightly different electron distributions, which couple slightly differently to the decoherence environment.

The amplification factor is:

$$A = \exp(-\alpha * \delta_{\gamma})$$

where δ_{γ} is the difference in decoherence rates between L and D forms. Even though δ_{γ} is tiny in absolute terms, the factor $\alpha \sim 1000$ amplifies it exponentially:

$$\begin{aligned} \delta_{\gamma} &\sim \text{PVED} / (\hbar * \omega_c) \sim 10^{-17} \text{ eV} / (10^{-14} \text{ eV}) \sim 10^{-3} \\ \alpha * \delta_{\gamma} &\sim 1000 * 10^{-3} = 1 \\ A &\sim \exp(-1) \sim 0.37 \end{aligned}$$

This means the D-form coherence is 37% of the L-form coherence (or vice versa, depending on the sign of the PVED for the specific molecular system). This is not a subtle effect. At the phase transition, where coherence determines catalytic viability, a 63% coherence disadvantage is lethal. The less-coherent enantiomer cannot sustain catalytic cycles. The more-coherent one can. Selection is complete within a single generation of the catalytic cycle.

The key insight from Paper 131 applies here: chirality selection is not a problem that needs a separate mechanism. It is an automatic consequence of the coherence phase transition. Any system that crosses γ_c will simultaneously become alive and homochiral. These are not two events. They are one.

6. Anomaly 4: Warm Little Pond vs Deep Sea Vent

Statement. Darwin proposed a "warm little pond." Modern candidates include hydrothermal vents (black smokers and alkaline vents like Lost City), tidal pools, ice surfaces, and even atmospheric aerosols. The debate has continued for decades because each environment has plausible chemistry. Where did life actually start?

Closure. The coherence framework answers this question with a prediction, not an assumption: life started wherever γ_{eff} first dropped below γ_c . This is a calculable criterion.

Consider the decoherence rate in each candidate environment:

Warm little pond (surface):

$$\gamma_{\text{pond}} = \gamma_{\text{thermal}} + \gamma_{\text{UV}} + \gamma_{\text{solvent}} + \gamma_{\text{dilution}}$$

Surface environments suffer UV-induced decoherence (γ_{UV} is large before the ozone layer), rapid thermal fluctuations (γ_{thermal} varies with weather cycles), full solvent exposure (γ_{solvent} is maximal in open water), and dilution of reactants (γ_{dilution} reduces molecular encounter rates). The total γ_{pond} is well above γ_c for most conditions.

Deep sea alkaline vent (subsurface):

$$\text{gamma_vent} = \text{gamma_thermal} + \text{gamma_mineral_shielded} + \text{gamma_gradient}$$

No UV ($\text{gamma_UV} = 0$ at depth). Stable temperature maintained by geothermal gradients (gamma_thermal is constant and tunable by location within the vent). Mineral matrices -- iron-nickel sulfides, silicates, calcium carbonates -- provide decoherence shielding ($\text{gamma_mineral_shielded} \ll \text{gamma_solvent}$). Chemical gradients across thin mineral walls provide sustained free energy input without disrupting coherence.

The critical feature of alkaline vents is that mineral micropores create natural compartments where gamma_eff can be maintained near gamma_c across geological time. The system does not need luck. It needs persistence. Given millions of micropores with slightly different gamma_eff values, some will sit at gamma_c . In those pores, coherence bootstraps.

Additionally, alkaline vents maintain pH gradients across thin mineral walls -- exactly the kind of proton-motive force that all modern life uses for energy transduction (chemiosmosis). The coherence framework explains why: a pH gradient across a mineral wall is a gamma_eff gradient. The low-gamma side sustains coherence. The high-gamma side provides chemical free energy. The wall is the boundary. This is protocellular metabolism.

Prediction. Deep sea alkaline vents are the origin site. Not because of chemical arguments (though those are strong -- see Russell and Hall, Martin and Russell). Because the coherence framework requires it. The calculation of gamma_eff in each candidate environment predicts that alkaline vents are the first environment on early Earth where gamma_eff sustainably drops below gamma_c .

7. Anomaly 5: Protocell Membrane Formation

Statement. Modern cells are defined by membranes -- lipid bilayers that separate interior from exterior. How did the first membranes form? Lipid vesicles self-assemble readily from fatty acids in laboratory conditions, but why would early molecular assemblies acquire membranes? What selective advantage did a membrane provide before there was complex metabolism to contain?

Closure. A membrane is a gamma_eff discontinuity. Inside the lipid bilayer, the dielectric environment is radically different from bulk water. The hydrophobic interior of the bilayer has a dielectric constant of approximately 2, compared to 80 for water. This means electromagnetic fluctuations -- a major source of decoherence for polar and charged molecules -- are suppressed by a factor of 40 inside the membrane-bounded space.

More precisely, the membrane creates a boundary condition on the electromagnetic vacuum fluctuation spectrum. Inside the membrane, the spectral density of fluctuations at biological frequencies is sharply reduced. This directly reduces gamma_eff for enclosed molecular assemblies:

$$\text{gamma_inside} = \text{gamma_outside} * (\text{epsilon_water} / \text{epsilon_membrane})^n$$

where n depends on the geometry and the specific decoherence mechanism ($n \sim 1$ for direct dielectric screening, $n \sim 2$ for fluctuation-mediated decoherence). For $n = 1$:

$$\text{gamma_inside} \sim \text{gamma_outside} * (2/80) = \text{gamma_outside} / 40$$

A forty-fold reduction in gamma_eff is enormous when $\alpha \sim 1000$. The coherence

enhancement is:

$$\begin{aligned} C_{\text{inside}} / C_{\text{outside}} &= \exp(-\alpha * (\gamma_{\text{inside}} - \gamma_{\text{outside}})) \\ &= \exp(-1000 * \gamma_{\text{outside}} * (1/40 - 1)) \\ &= \exp(1000 * \gamma_{\text{outside}} * 39/40) \end{aligned}$$

For γ_{outside} near γ_c , this produces orders-of-magnitude increases in coherence.

This means membrane formation is not a puzzle requiring explanation. It is thermodynamically driven by the coherence framework. A system of molecules near the coherence phase transition will spontaneously compartmentalize because compartmentalization reduces γ_{eff} , which increases coherence, which increases the system's ability to sustain catalytic cycles that produce the membrane components. The membrane is self-reinforcing.

This is why lipid bilayers self-assemble so readily: self-assembly is the system minimizing its total decoherence by creating γ_{eff} discontinuities. The "selective advantage" of a membrane is not containment of metabolites (the standard explanation). The selective advantage is decoherence reduction. Containment is a side effect. Coherence is the driver.

8. Anomaly 6: Metabolism-First vs Replication-First

Statement. The origin-of-life community has debated for decades whether metabolism or replication came first. The metabolism-first camp (Wächtershäuser, Russell, Morowitz) argues that autocatalytic chemical cycles preceded genetic information. The replication-first camp (Orgel, Szostak, Joyce) argues that self-replicating molecules (RNA) preceded metabolic networks. Neither camp has produced a convincing experimental demonstration of its scenario in isolation.

Closure. The debate is dissolved. Neither metabolism nor replication came first. Coherence came first.

Both metabolic cycles and template replication are consequences of sustained coherence. A coherent catalytic cycle IS metabolism: a set of reactions that sustains itself through coherent coupling of reaction intermediates. A coherent template-copying process IS replication: a molecular assembly that produces copies of an information-bearing molecule through coherent base-pairing and polymerization.

At the coherence phase transition $\gamma_{\text{eff}} = \gamma_c$, both capabilities emerge simultaneously because both are manifestations of the same underlying physics: sustained quantum coherence across a molecular network.

Consider why:

Metabolism as coherent catalysis. A metabolic cycle requires that the product of reaction N serves as the catalyst or substrate for reaction N+1, and that the cycle closes -- the product of the last reaction regenerates the input to the first. In an incoherent (thermal) system, each reaction proceeds independently. The probability that all reactions in a cycle of length N proceed in sequence is the product of individual probabilities, which shrinks exponentially with N. In a coherent system, the reactions are coupled. The intermediate states are superposed. The cycle does not proceed step-by-step. It proceeds as a coherent process across the entire network. This is why metabolism works: not because each enzyme is efficient in isolation, but because the metabolic network maintains coherence across multiple reaction steps.

Replication as coherent copying. Template-directed polymerization requires that each incoming monomer "reads" the template and selects the correct complementary base. In an incoherent system, this is a thermally-driven process with an error rate determined by the free energy difference between correct and incorrect base pairs (approximately 2-4 kT, giving error rates of 10^{-1} to 10^{-2} per base). In a coherent system, the incoming monomer's quantum state couples to the template's quantum state, producing an amplified selectivity through coherent discrimination. The error rate drops to $\exp(-\alpha * \text{delta_gamma_mismatch})$, where $\text{delta_gamma_mismatch}$ is the decoherence rate difference between matched and mismatched base pairs. With $\alpha \sim 1000$, even small values of $\text{delta_gamma_mismatch}$ produce enormous selectivity.

Both capabilities require the same thing: $\text{gamma_eff} < \text{gamma_c}$. Both emerge at the same transition. The metabolism-replication debate assumed they were separate capabilities requiring separate origins. The coherence framework reveals they are one capability -- sustained molecular coherence -- expressed in two ways.

9. Anomaly 7: The Faint Young Sun Paradox (Biological Angle)

Statement. The Sun was approximately 30% less luminous 4 billion years ago than it is today. Standard climate models predict that early Earth should have been frozen. Yet geological evidence shows liquid water and thriving microbial life by 3.8 billion years ago, possibly 4.1 billion. The standard resolution involves greenhouse gases (CO₂, CH₄, N₂O at higher concentrations). This paper addresses the biological angle: how did early life thrive with less energy input?

Closure. Early life was more coherent than modern life. This is counterintuitive only if one assumes that evolution optimizes coherence. It does not. Evolution optimizes fitness, which is a complex function of coherence, robustness, adaptability, and reproductive rate. Modern life operates well above gamma_c -- it has headroom. Early life operated near gamma_c -- at the edge of the phase transition.

But "near gamma_c " means "near maximal coherence enhancement." The exponential $\exp(-\alpha * \text{gamma_eff})$ is steepest near gamma_c . Small reductions in gamma_eff near the transition produce large gains in C. Early organisms, living near the phase boundary, extracted more catalytic work per unit of coherence than modern organisms, which operate in the plateau region far from gamma_c .

Additionally, the early ocean environment provided lower gamma_eff than modern oceans:

$$\text{gamma_early} = \text{gamma_thermal} + \text{gamma_dissolved} + \text{gamma_radiation}$$

$$\text{gamma_modern} = \text{gamma_thermal} + \text{gamma_dissolved}(\text{higher}) + \text{gamma_radiation} + \text{gamma_O}_2$$

Early oceans had lower dissolved mineral content (less continental weathering had occurred). No dissolved oxygen (a potent source of chemical decoherence through reactive oxygen species). Different atmospheric composition (less UV at the surface due to thicker CO₂ atmosphere, different spectral distribution). The net effect: $\text{gamma_early} < \text{gamma_modern}$ for subsurface aqueous environments.

Higher coherence means:

1. More efficient catalysis per enzyme molecule -- fewer enzyme copies needed, less protein synthesis required, less energy consumed.
2. More efficient energy transduction -- chemiosmotic coupling with less proton

leakage across membranes (tighter coherence at the membrane boundary).

3. Lower maintenance metabolism -- less energy spent repairing decoherence-induced damage (oxidative damage did not yet exist; thermal damage was reduced by higher coherence).

The result: early life required less energy input to sustain itself. The faint young Sun was not a problem for organisms running near the coherence phase transition. They were, in a precise physical sense, more efficient than modern organisms. The 30% luminosity deficit is offset by higher coherence efficiency.

This predicts a testable pattern: as the Sun brightened over geological time, organisms evolved AWAY from the phase boundary -- increasing γ_{eff} (through oxidative metabolism, higher metabolic rates, more complex cellular machinery with more decoherence sources) while maintaining viability through the increasing energy budget. The history of life is the history of moving away from γ_c , trading coherence efficiency for complexity and adaptability.

10. The Coherence Bootstrap: Synthesis

The seven anomalies addressed in this paper are not independent puzzles. They are aspects of a single phenomenon: the coherence phase transition at $\gamma_{\text{eff}} = \gamma_c$.

The bootstrap proceeds as follows:

1. Environment preparation. Geological processes (hydrothermal activity, mineral precipitation) create microporous environments where γ_{eff} approaches γ_c . No biology is required for this step. It is geology.
2. Chemical accumulation. Ordinary prebiotic chemistry (Miller-Urey synthesis, Fischer-Tropsch synthesis on mineral surfaces, delivery by meteorites) produces amino acids, nucleotides, lipids, and small organic molecules. These accumulate in mineral micropores. No coherence is required for this step. It is chemistry.
3. Phase transition. In some micropores, the combination of molecular concentration, mineral shielding, and stable temperature brings γ_{eff} below γ_c . Coherent catalytic cycles bootstrap. Simultaneously: metabolism emerges (coherent catalysis), information copying emerges (coherent replication), chirality locks (coherent amplification of PVED), and membrane formation begins (coherence-driven compartmentalization).
4. Consolidation. Once coherent, the system produces its own decoherence shields (first mineral-organized, then peptide-based, then protein-based). Each improvement in shielding reduces γ_{eff} further below γ_c , increasing robustness. The system moves from barely-alive (at γ_c) to robustly-alive (well below γ_c). This is not Darwinian evolution yet -- it is coherence-driven self-improvement.
5. Darwinian threshold. Once the system achieves sufficient replication fidelity (through improved coherence in template copying), Darwinian evolution begins. Error rates drop below the error catastrophe threshold. Information accumulates across generations. Coherence-driven improvement gives way to evolution-driven improvement. Life, as we recognize it, is underway.

The bootstrap is not improbable. It is inevitable, given sufficient time and the right geological setting. The coherence phase transition is as deterministic as the transition from water to ice at 273 K. It does not require luck, miracles, or

extraordinary coincidence. It requires carbon chemistry at 310 K in a mineral-shielded aqueous environment with stable free energy input. These conditions existed on early Earth. Therefore, life arose.

11. Predictions

The coherence bootstrap framework generates falsifiable predictions:

Prediction 1. Synthetic origin-of-life experiments will succeed only when they achieve $\gamma_{\text{eff}} < \gamma_{\text{c}}$. Experiments in bulk solution (high γ_{eff}) will continue to produce interesting chemistry but not self-sustaining systems. Experiments in mineral-shielded microporous environments with stable chemical gradients will succeed. The key experimental variable is not temperature, pH, or reactant concentration. It is γ_{eff} .

Prediction 2. The transition from chemistry to life in successful experiments will be sharp, not gradual. There will be a measurable threshold below which the system self-organizes and above which it does not. This threshold corresponds to γ_{c} .

Prediction 3. Life that arises in such experiments will be homochiral from the start. Chirality selection and abiogenesis will occur simultaneously, not sequentially.

Prediction 4. Membrane formation will occur spontaneously at the phase transition, not as a later evolutionary addition. The membrane will form because the system minimizes γ_{eff} , not because of any selective advantage related to containment.

Prediction 5. Early life analogs (organisms engineered or evolved to operate near γ_{c}) will show higher catalytic efficiency per enzyme molecule than modern organisms, but lower robustness to environmental perturbation.

Prediction 6. The ratio of metabolic efficiency to energy input in ancient microbial lineages (measured through comparative biochemistry of deeply branching organisms) will be systematically higher than in modern organisms, consistent with operation closer to γ_{c} .

12. What Life Is

This paper permits a definition of life that is precise, physical, and non-circular:

Life is a molecular system operating below the critical decoherence rate γ_{c} , where coherent catalytic cycles, coherent information copying, and coherent self-organization are self-sustaining.

This definition:

- Distinguishes life from non-life by a measurable physical quantity (γ_{eff} relative to γ_{c}).
- Does not require reproduction, metabolism, or evolution as defining criteria -- these are consequences of coherence, not prerequisites.
- Applies to carbon-based life at 310 K and can be extended to any chemistry at any temperature by recalculating α and γ_{c} for the relevant molecular physics.
- Explains why viruses are ambiguously alive (they operate above γ_{c} in isolation but below γ_{c} when coupled to a host cell's decoherence-shielding machinery).

- Explains why fire, crystals, and autocatalytic chemical reactions are not alive despite sharing some surface features with life (they do not operate below γ_c for their respective molecular systems).

13. Conclusion

Seven anomalies in origin-of-life research -- abiogenesis, RNA world fragility, chirality selection, the venue debate, membrane formation, the metabolism-replication priority question, and the faint young sun paradox -- are closed by the coherence decay function $C = C_0 * \exp(-\alpha * \gamma_{eff})$.

The closures are not ad hoc. They follow from a single physical principle applied to carbon chemistry at 310 K. The chain $G \rightarrow T(310K) \rightarrow \lambda_{dB}(0.1 \text{ nm}) \rightarrow \alpha \sim 1000 \rightarrow C \rightarrow \text{life}$ contains no free parameters beyond those fixed by fundamental physics and the choice of chemistry.

Life is not mysterious. Life is not improbable. Life is not the result of an extraordinary accident in an ordinary universe. Life is the coherence phase transition. It is as inevitable as ice, as predictable as superconductivity, and as sharp as any other phase transition in physics.

The question was never "how did life begin?" The question was always "what is the order parameter?" The answer is coherence.

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