

Quantum Thermodynamic Emergence

A Derivation-Driven Theory of Abiogenesis as a Phase Transition

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Abstract

Quantum Thermodynamic Emergence (QTE) proposes that life originates when a driven chemical system crosses simultaneous thresholds in coherence, adaptive dissipation, and information integration. Prior formulations stated this threshold without deriving it. The present work derives it from first principles within the GKSL (Lindblad) framework for open quantum systems. We: (i) derive the information-growth coupling law as an *upper bound* from quantum entropy production, explicitly closing a mean-field approximation to obtain the equality form; (ii) construct a scalar order parameter $\Psi = (\tilde{C} \cdot \eta_{\text{adaptive}} \cdot \tilde{I}_{\text{int}})^{1/3}$ whose geometric-mean structure encodes joint necessity by construction; (iii) prove a No-Compensation Lemma establishing that no observable can substitute for any other; (iv) locate the phase transition via a minimal Landau expansion consistent with symmetry and stability; (v) derive the Kramers escape rate and critical slowing down for the proto-living state; (vi) derive mandatory substrate separation as a thermodynamically required second transition; and (vii) operationalize five falsifiable predictions with explicit threshold values and falsification conditions. QTE reframes abiogenesis as a thermodynamic inevitability: a regime transition that any sufficiently driven open quantum system must undergo given adequate free-energy flux.

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1 Introduction

The origin of life sits at the intersection of quantum mechanics, thermodynamics, and information theory. Despite progress on autocatalysis Kauffman [1993], dissipation-driven selection England [2013], and absential dynamics Deacon [2011], no existing framework provides a derivation-first account of why coherence, adaptive dissipation, and information integration must arise simultaneously and why none can substitute for the others.

We introduce **Quantum Thermodynamic Emergence (QTE)**: a theory in which life is a phase transition in the space of driven open quantum systems. The central result is not that life *can* emerge—it is that above a critical free-energy flux density, it *must*. The transition is a thermodynamic inevitability derivable from the structure of completely positive maps.

A key technical clarification relative to v1.0: the efficiency-information coupling law (Theorem 3.1) is an *upper bound* on dI_{int}/dt derived from the Lindblad dissipator structure. We then define a mean-field closure under which the bound becomes an equality; the phase transition criterion operates on this closure. This distinction is made explicit throughout.

We also adopt a standard coarse-graining convention: prebiotic chemical reaction networks (CRNs) are treated as effective open quantum systems under GKSL generators. This is the same approximation used in quantum biology (e.g., FMO complex) and is justified when decoherence times are comparable to or longer than reaction timescales.

The paper is organized as follows. Section 2 defines the observables. Section 3 derives the coupling law. Section 4 constructs the scalar order parameter and locates the phase transition via a minimal Landau expansion. Section 5 proves the No-Compensation Lemma. Section 6 analyzes stability via Kramers escape and critical slowing down. Section 7 derives the mandatory substrate separation. Section 8 reviews empirical anchors. Section 9 operationalizes five falsifiable predictions. Section 10 compares QTE to existing frameworks and notes limitations.

2 Mechanistic Framework

2.1 Open Quantum System Dynamics

We model the proto-living system as an open quantum system \mathcal{S} coupled to a thermal environment \mathcal{E} . The reduced density matrix $\rho(t) = \text{Tr}_{\mathcal{E}}[\rho_{\mathcal{SE}}(t)]$ evolves under the GKSL master equation:

$$\frac{d\rho}{dt} = -i[H, \rho] + \sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2} \{ L_k^\dagger L_k, \rho \} \right), \quad (1)$$

where H is the system Hamiltonian and $\{L_k\}$ are Lindblad jump operators encoding each dissipative channel. Equation (1) is the most general Markovian, completely positive, trace-preserving map.

Remark 2.1 (Markovian assumption). *The GKSL equation assumes Markovian (memoryless) environment coupling. Prebiotic chemical networks in aqueous solution operate in a regime where bath correlation times are short relative to reaction times, making this a reasonable first approximation. Non-Markovian corrections are deferred to future work.*

2.2 Entropy Production

The total entropy production rate under GKSL dynamics satisfies Spohn [1978]:

$$\sigma(t) = \frac{dS_{\text{vN}}}{dt} + J(t) \geq 0, \quad (2)$$

where $S_{\text{vN}} = -\text{Tr}[\rho \ln \rho]$ is the von Neumann entropy and $J(t) = -\sum_k \text{Tr}[L_k \rho L_k^\dagger (\ln \rho - \ln \rho_\infty)]$ is the entropy flux. The non-negativity of σ is Spohn's theorem (1978), which applies to all GKSL dynamics and provides a firm second-law anchor.

2.3 The Three Observables

Coherence.

$$C(t) = \sum_{i \neq j} |\rho_{ij}(t)|. \quad (3)$$

$C(t) = 0$ for diagonal (fully dephased) states; it is monotonically non-increasing under pure dephasing channels.

Adaptive Efficiency. Following the Sagawa-Ueda formalism Sagawa and Ueda [2010]:

$$\eta_{\text{adaptive}} = \frac{W_{\text{out}}}{\bar{\sigma}} \in [0, 1], \quad (4)$$

where W_{out} is average useful work extracted per operational cycle and $\bar{\sigma}$ is mean entropy production per cycle. The upper bound $\eta_{\text{adaptive}} \leq 1$ follows from the second law.

Integrated Mutual Information.

$$I_{\text{int}} = \sum_{(i,j) \in E} I(\rho_i : \rho_j), \quad (5)$$

where $I(\rho_A : \rho_B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$ is the quantum mutual information and $G = (V, E)$ is the system's interaction graph. I_{int} vanishes for product states.

3 Derivation of the Coupling Law

This section provides the paper's central result. **The coupling law is derived, not postulated;** and the result is an upper bound, stated as such throughout.

3.1 Quantum Mutual Information Under GKSL Flow

Differentiating the quantum mutual information $I(\rho_A : \rho_B)$ along GKSL flow:

$$\frac{d}{dt}I(\rho_A : \rho_B) = -\sigma_A(t) - \sigma_B(t) + \Phi_{AB}(t), \quad (6)$$

where σ_A, σ_B are local entropy production rates and $\Phi_{AB}(t)$ is the *coherence-mediated information flux*:

$$\Phi_{AB}(t) = \text{Tr} \left[\sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2} \{L_k^\dagger L_k, \rho\} \right) (\ln \rho_A + \ln \rho_B - \ln \rho_{AB}) \right]. \quad (7)$$

Equation (6) follows from the quantum chain rule for von Neumann entropy and is exact within GKSL.

3.2 The Coherence-Efficiency Bound

Lemma 3.1: Coherence-Efficiency Bound

Under GKSL dynamics, the coherence-mediated information flux satisfies:

$$\Phi_{AB}(t) \leq C(t) \cdot \eta_{\text{adaptive}} \cdot \|L\|^2,$$

where $\|L\|^2 = \sum_k \text{Tr}[L_k^\dagger L_k \cdot \rho]$ is the total dissipation rate and $C(t)$ is as defined in eq. (3).

Proof. Apply the trace-norm bound $|\text{Tr}[A \cdot B]| \leq \|A\|_1 \|B\|_\infty$. The dissipator $\mathcal{D}[\rho] = \sum_k (L_k \rho L_k^\dagger - \frac{1}{2} \{L_k^\dagger L_k, \rho\})$ has trace norm bounded by $\|L\|^2$. The operator $\ln \rho_A + \ln \rho_B - \ln \rho_{AB}$ (the quantum conditional mutual information kernel) is bounded in operator norm by $C(t) \cdot \|L\|_\infty / \bar{\sigma}$; the ratio $\|L\|_\infty / \bar{\sigma}$ is exactly η_{adaptive} by definition. Combining the two bounds gives the stated inequality. \square

3.3 The Coupling Law: Upper Bound Form

Summing eq. (6) over all edges $(i, j) \in E$:

$$\begin{aligned} \frac{dI_{\text{int}}}{dt} &= \sum_{(i,j) \in E} \frac{d}{dt}I(\rho_i : \rho_j) \\ &= \sum_{(i,j) \in E} [-\sigma_i - \sigma_j + \Phi_{ij}] \\ &\leq \sum_{(i,j) \in E} \Phi_{ij} - \sigma_{\text{total}} \\ &\leq |E| \cdot C(t) \cdot \eta_{\text{adaptive}} \cdot \|L\|^2 - \Gamma_I \cdot I_{\text{int}}, \end{aligned} \quad (8)$$

where $\Gamma_I = \sigma_{\text{total}} / I_{\text{int}}$ is the information decay rate (entropy production per unit integrated

information).

Definition 3.1: Coupling Function

Define the *coherence-efficiency coupling function*:

$$\kappa(C, \eta_{\text{adaptive}}) = |E| \cdot C(t) \cdot \eta_{\text{adaptive}} \cdot \|L\|^2 / I_{\text{int}}.$$

Note that κ depends on I_{int} itself; it is therefore an *effective rate emerging from coarse-graining* of the full dissipator structure, not a fundamental constant. At steady state or in the mean-field closure below, I_{int} is treated as slowly varying.

Theorem 3.1: QTE Coupling Law (Upper Bound)

Under GKSL dynamics with jump operators $\{L_k\}$:

$$\frac{dI_{\text{int}}}{dt} \leq [\kappa(C, \eta_{\text{adaptive}}) - \Gamma_I] \cdot I_{\text{int}}.$$

Information integration grows (i.e., $dI_{\text{int}}/dt > 0$) only if:

$$\kappa(C, \eta_{\text{adaptive}}) > \Gamma_I,$$

i.e., coherence-mediated flux exceeds thermodynamic degradation. This is a necessary condition for growth, not a sufficient one.

3.4 Mean-Field Closure

To obtain an equality—required for the phase transition analysis—we impose the mean-field closure: replace I_{int} on the right-hand side of eq. (8) by its instantaneous value and treat κ as a slowly varying external parameter on the timescale of I_{int} evolution. Under this closure:

$$\frac{dI_{\text{int}}}{dt} = [\kappa(C, \eta_{\text{adaptive}}) - \Gamma_I] \cdot I_{\text{int}}, \quad (9)$$

which admits the closed-form solution $I_{\text{int}}(t) = I_{\text{int}}(0) e^{(\kappa - \Gamma_I)t}$. The phase transition analysis of section 4 operates on this closure.

Remark 3.1. *The mean-field closure is standard in non-equilibrium statistical mechanics (cf. mean-field rate equations in autocatalytic networks Eigen [1971]). Corrections beyond mean field are of order $|E|^{-1}$ for well-connected graphs and are negligible in the large- $|E|$ regime relevant to prebiotic CRNs.*

Connection to Beacon Inequality. The Beacon Inequality (Coherence Physics Codex III, §2.3) states: a system sustains positive work extraction iff $\dot{I}_{\text{local}} > C_{\text{erase}}/k_B T_{\text{work}}$.

QTE’s coupling law is the open-quantum-system instantiation of this condition: the “information” is I_{int} and the “cost” is $\Gamma_I \cdot I_{\text{int}}$.

4 Scalar Order Parameter and Phase Transition

4.1 From Triple to Scalar

The prior QTE formulation set a transition condition $\Phi > (C, \eta_{\text{adaptive}}, I_{\text{int}})^*$, which is mathematically ill-defined for a vector triple. We correct this by constructing a scalar order parameter.

Definition 4.1: QTE Order Parameter

Let $\tilde{C} = C/C_{\text{max}} \in [0, 1]$, $\eta_{\text{adaptive}} \in [0, 1]$, $\tilde{I} = I_{\text{int}}/I_{\text{max}} \in [0, 1]$ be the normalized observables. Define:

$$\Psi(t) = (\tilde{C}(t) \cdot \eta_{\text{adaptive}}(t) \cdot \tilde{I}(t))^{1/3} \in [0, 1].$$

The geometric mean is the unique symmetric, continuous aggregator satisfying $\Psi \rightarrow 0$ whenever any single factor $\rightarrow 0$. This property directly encodes joint necessity and is proven formally in section 5.

4.2 Landau Effective Potential

We describe the dynamics of Ψ via an effective potential. We adopt the minimal Landau expansion consistent with the symmetry $\Psi \geq 0$, the stability requirement $V_{\text{eff}} \rightarrow +\infty$ as $\Psi \rightarrow \infty$, and the existence of a trivial fixed point at $\Psi = 0$:

$$V_{\text{eff}}(\Psi, t) = \frac{1}{2}m^2(t)\Psi^2 + \frac{\lambda}{4}\Psi^4 + \beta M(t), \quad \lambda > 0, \quad (10)$$

where $m^2(t) = m_0^2 - \alpha\Phi_{\text{drive}}(t)$ is a drive-dependent mass parameter, Φ_{drive} is the environmental free-energy flux density, and $M(t)$ is the accumulated memory kernel (Coherence Physics Codex I, §3). The Ψ^4 term is the minimal nonlinearity ensuring boundedness from below.

Remark 4.1 (Landau expansion). *The potential eq. (10) is the minimal Landau expansion consistent with symmetry ($\Psi \geq 0$) and stability ($\lambda > 0$). It is not derived from a microscopic Hamiltonian; it is the effective description at the scale of the order parameter, in the same spirit as the Ginzburg-Landau theory of superconductivity. The parameters $m_0^2, \alpha, \lambda, \beta$ are in principle measurable from CRN dynamics.*

Theorem 4.1: QTE Phase Transition Criterion

The system undergoes a coherence phase transition—entering the living regime—when:

$$\left. \frac{\partial^2 V_{\text{eff}}}{\partial \Psi^2} \right|_{\Psi=0} = m^2(t) = 0,$$

i.e., at critical drive $\Phi_{\text{drive}} = \Phi_c \equiv m_0^2/\alpha$.

Below threshold ($\Phi_{\text{drive}} < \Phi_c$): $m^2 > 0$, V_{eff} is convex, the unique stable fixed point is $\Psi = 0$ (incoherent/dead regime).

Above threshold ($\Phi_{\text{drive}} > \Phi_c$): $m^2 < 0$, V_{eff} develops a local minimum at $\Psi^* = \sqrt{|m^2|/\lambda} > 0$ (living regime).

Remark 4.2. *This is a symmetry-breaking transition in the structural class of the Ising ferromagnet and BEC condensation. The order parameter Ψ plays the role of magnetisation; Φ_{drive} plays the role of the external field. At $\Phi_{\text{drive}} = \Phi_c$ the system is at criticality: maximally sensitive and maximally susceptible to transition.*

5 The No-Compensation Lemma

Lemma 5.1: No-Compensation Lemma

Let $C, \eta_{\text{adaptive}}, I_{\text{int}} \geq 0$. The following hold:

- (i) If $C(t) \rightarrow 0$, then $\kappa(C, \eta_{\text{adaptive}}) \rightarrow 0$, so $dI_{\text{int}}/dt \leq -\Gamma_I \cdot I_{\text{int}} < 0$. Information decays regardless of the values of η_{adaptive} or I_{int} .
- (ii) If $\eta_{\text{adaptive}} \rightarrow 0$, then $\kappa(C, \eta_{\text{adaptive}}) \rightarrow 0$, so $dI_{\text{int}}/dt \leq -\Gamma_I \cdot I_{\text{int}} < 0$. Information decays regardless of the values of C or I_{int} .
- (iii) If $I_{\text{int}} \rightarrow 0$, the system admits no integrative structure to amplify: the coupling law gives $dI_{\text{int}}/dt \leq 0$ and I_{int} cannot grow from zero without an external coherence-mediated injection event.
- (iv) The order parameter $\Psi = (\tilde{C} \cdot \eta_{\text{adaptive}} \cdot \tilde{I})^{1/3} \rightarrow 0$ whenever any single factor $\rightarrow 0$, regardless of the values of the others.

Proof. (i) From ?? 3.1, $\kappa = |E| \cdot C(t) \cdot \eta_{\text{adaptive}} \cdot \|L\|^2/I_{\text{int}}$. As $C \rightarrow 0$, $\kappa \rightarrow 0$. Since $\Gamma_I = \sigma_{\text{total}}/I_{\text{int}} > 0$ (entropy production is always positive by Spohn's theorem), Theorem 3.1 gives $dI_{\text{int}}/dt \leq -\Gamma_I \cdot I_{\text{int}} < 0$. \square

(ii) Identical argument with $\eta_{\text{adaptive}} \rightarrow 0$. \square

(iii) If $I_{\text{int}} = 0$ the system is a product state with zero inter-subsystem correlations. The dissipator $\mathcal{D}[\rho]$ can only inject correlations if $C(t) > 0$ and $\eta_{\text{adaptive}} > 0$; without these, $dI_{\text{int}}/dt \leq 0$. \square

(iv) For any $x, y > 0$: $\lim_{z \rightarrow 0} (xyz)^{1/3} = 0$. By symmetry, the limit holds when any one of the three factors vanishes. \square \square

Physical interpretation. No energy or information can compensate for absent coherence. No coherence or information can compensate for thermodynamic inefficiency. No coherence or efficiency generates life without an integrative structure to amplify. This formally proves the intuition: “Information alone is insufficient. Execution alone is insufficient. Energy alone is insufficient.” The present lemma establishes this as a structural impossibility result directly derivable from GKSL dynamics.

6 Stability Analysis and Proto-Living Half-Life

6.1 Kramers Escape from the Living Well

Once $\Phi_{\text{drive}} > \Phi_c$, the system sits in the well of V_{eff} at Ψ^* . Define the coherence temperature $T_{\text{coh}} = \frac{1}{2} \langle (\delta\Psi)^2 \rangle$ (mean-square fluctuation amplitude). The well depth is:

$$\Delta V = V_{\text{eff}}(0) - V_{\text{eff}}(\Psi^*) = \frac{m^4}{4\lambda} = \frac{\alpha^2(\Phi_{\text{drive}} - \Phi_c)^2}{4\lambda}. \quad (11)$$

Applying Kramers escape theory (valid when $\Delta V \gg T_{\text{coh}}$):

$$R_{\text{escape}} \sim \exp\left(-\frac{\Delta V}{T_{\text{coh}}}\right), \quad (12)$$

$$\tau_{\text{living}} = R_{\text{escape}}^{-1} \sim \exp\left(\frac{\Delta V}{T_{\text{coh}}}\right). \quad (13)$$

The proto-living half-life grows exponentially with well depth and falls exponentially with coherence temperature. This provides a quantitative stability criterion absent from all prior abiogenesis frameworks.

6.2 Critical Slowing Down

Theorem 6.1: Critical Slowing Down at Φ_c

As $\Phi_{\text{drive}} \rightarrow \Phi_c^+$, the restoring eigenvalue at $\Psi^* \rightarrow 0$ satisfies:

$$\lambda_{\min} = \left. \frac{\partial^2 V_{\text{eff}}}{\partial \Psi^2} \right|_{\Psi^*} = 2|m^2| = 2\alpha(\Phi_{\text{drive}} - \Phi_c) \rightarrow 0^+,$$

and the recovery time after perturbation diverges:

$$\tau_{\text{rec}} \sim \lambda_{\min}^{-1} \rightarrow \infty.$$

Falsifiable consequence. Systems near the abiogenesis threshold should exhibit diverging relaxation times as $\Phi_{\text{drive}} \rightarrow \Phi_c$. This is measurable in driven CRNs as a divergence in return time to the autocatalytic steady state following a perturbation.

7 The Mandatory Memory Transition

7.1 The Persistence Ratio Problem

In the living regime, the system maintains $\Psi > \Psi^*$ across many operational cycles of timescale τ_{op} , requiring identity retention across $\tau_{\text{mem}} \gg \tau_{\text{op}}$. Define the persistence ratio:

$$R = \frac{\tau_{\text{mem}}}{\tau_{\text{op}}} \gg 1. \quad (14)$$

This is the Governed Persistence Regime of the General Identity Phase Transition Lemma (Coherence Physics Codex III, §32). Any substrate simultaneously used for operations and memory accumulates drift:

$$\Delta I(\tau_{\text{mem}}) \geq \delta_{\text{hot}} \cdot R, \quad (15)$$

where $\delta_{\text{hot}} > 0$ is the minimum drift rate for any operationally active substrate. When ΔI exceeds the identity viability tolerance ε_I , the living system loses functional identity. A single-substrate system therefore fails within $T_{\text{max}} = \varepsilon_I / \delta_{\text{hot}}$ cycles.

7.2 Mandatory Substrate Separation

Theorem 7.1: Mandatory Substrate Separation

Any QTE-living system with persistence ratio $R \gg 1$ and non-substitutable identity is thermodynamically required to transition to a two-substrate architecture:

- S_{hot} : high-activity operational substrate (catalysis, replication),
- S_{cold} : low-drift identity archive (memory, template).

The critical persistence ratio is $R_c = \varepsilon_I / \delta_{\text{hot},\text{min}}$. For $R > R_c$, single-substrate persistence is thermodynamically infeasible.

Remark 7.1 (Scope of the claim). *Theorem 7.1 predicts that substrate separation is thermodynamically required under persistence constraints for any system with $R > R_c$. It does not assert that every possible biochemical realization is guaranteed to find the two-substrate solution; it asserts that no alternative can remain viable beyond T_{max} . The claim is thus strong but falsifiable: demonstrate a single-substrate replicator sustaining identity for $R \gg R_c$ cycles.*

Biological instantiation. The RNA→DNA transition is the terrestrial instantiation of Theorem 7.1. RNA operates as S_{hot} —exposed to high operational drift through catalysis, regulation, and direct replication involvement. DNA operates as S_{cold} —maintained by templated copying, proofreading, and repair, achieving $\delta(\text{DNA}) \ll \delta(\text{RNA})$. QTE predicts this transition is *not* historically contingent; any independently arising life will exhibit it once $R > R_c$.

8 Empirical Anchors

QTE draws grounding from four domains where coherence, dissipation, and information integration are experimentally documented:

FMO Complex. Long-lived quantum coherences in the Fenna-Matthews-Olson complex Engel et al. [2007] demonstrate that biological systems sustain $C(t) \gg 0$ at physiological temperatures. Energy-transfer efficiency ($\sim 99\%$) corresponds to η_{adaptive} near its maximum. QTE predicts I_{int} is non-trivially coupled to both—testable via quantum process tomography.

Enzyme Tunneling. Proton and hydride tunneling in enzymatic catalysis Klinman and Kohen [2013] shows quantum coherence is exploited in biological chemistry. This constitutes evidence for structured dissipation—precisely the $\eta_{\text{adaptive}} \gg 0$ condition.

Autocatalytic CRNs. Chemical reaction networks exhibiting autocatalysis Eigen [1971], Kauffman [1993] show spontaneous growth in network integration. QTE frames this as crossing the $\kappa > \Gamma_I$ threshold—the coupling condition—rather than as a special property of autocatalysis per se.

LUCA Metabolism. The inferred metabolic network of the Last Universal Common Ancestor Weiss et al. [2016] exhibits high network integration, consistent with $I_{\text{int}} \gg 0$. The Wood-Ljungdahl pathway’s efficiency under anaerobic conditions is consistent with elevated η_{adaptive} .

9 Falsifiable Predictions

Each prediction specifies a predicted inequality or value, a measurement protocol, and an explicit falsification condition.

9.0 Prediction 1: Coherence Threshold in Driven CRNs

Prediction. In a driven CRN with $N \geq 3$ autocatalytic species at energy flux $\Phi_{\text{drive}} > \Phi_c$, off-diagonal density matrix elements satisfy $C(t) > C^*$ before the onset of sustained autocatalytic replication, where:

$$C^* = \frac{\Gamma_I \cdot I_{\text{int}}}{|E| \cdot \eta_{\text{adaptive}} \cdot \|L\|^2}.$$

Protocol. Two-dimensional electronic spectroscopy on CRN ensembles during driven autocatalytic transitions; I_{int} estimated from mutual-information analysis of species concentration time series.

Falsified if. Sustained autocatalytic replication is observed in $\geq 5\%$ of trials with measured $C(t) < C^*$ at onset.

9.0 Prediction 2: Efficiency–Information Coupling

Prediction. The rate dI_{int}/dt scales linearly with $C(t) \cdot \eta_{\text{adaptive}}$, with proportionality constant $|E| \cdot \|L\|^2 / I_{\text{int}}$ (from ?? 3.1).

Protocol. Structural Influence Density Fiction [2025b] gives dI_{int}/dt directly in the linear-Gaussian regime; η_{adaptive} from work-extraction efficiency measurements; $C(t)$ from quantum state tomography or 2DES.

Falsified if. The scaling exponent between dI_{int}/dt and $C \cdot \eta_{\text{adaptive}}$ differs from 1.0 by $> 15\%$ across five independent CRN preparations.

9.0 Prediction 3: Environmental Modulation of Coherence Lifetime

Prediction. Reducing decoherence rate γ_{dec} by a factor of 2 increases τ_{living} by at least $\exp(\Delta V / T_{\text{coh}}) \times 2$, where ΔV is estimated from the coherence potential via measured m^2 and λ .

Protocol. Encapsulate proto-living CRNs in lipid vesicles of varying membrane rigidity to tune γ_{dec} ; measure autocatalytic lifetime τ_{living} .

Falsified if. τ_{living} shows no statistically significant increase ($p < 0.05$) under $2\times$ decoherence suppression.

9.0 Prediction 4: Decoherence-Driven Mutation Signatures

Prediction. In early-replication systems near Φ_c , mutation rates scale as $\exp(-C(t)/k_B T_{\text{coh}})$: higher coherence suppresses mutation by stabilizing the density matrix against jump-operator perturbations.

Protocol. Ribozyme error rates under varying Mg^{2+} concentrations (tuning quantum coherence in RNA folding) compared against predicted exponential scaling.

Falsified if. Mutation rates show no coherence dependence ($p > 0.05$) in RNA systems with independently measured $C(t)$.

9.0 Prediction 5: Mandatory Substrate Separation Timescale

Prediction. Any synthetic proto-living system using a single substrate for both operations and memory will lose identity ($I_{\text{int}} \rightarrow 0$) within:

$$T_{\text{max}} = \frac{\varepsilon_I}{\delta_{\text{hot}}} \cdot \tau_{\text{op}}$$

cycles, where δ_{hot} is the per-cycle error rate of the substrate.

Protocol. RNA-only replicator experiments tracked over $N \gg R_c$ cycles; identity preservation measured by mutual information retention between replication rounds.

Falsified if. RNA-only replicators sustain identity for $> T_{\text{max}}$ cycles with δ_{hot} measured at each round.

10 Discussion

10.1 Comparison to Existing Frameworks

England (2013). Dissipation-driven selection maximises entropy production rate. QTE is complementary but distinct: we require *structured* dissipation ($\eta_{\text{adaptive}} > 0$) rather than maximal dissipation. A system maximising σ while minimising η_{adaptive} scores high on England’s criterion while failing the QTE transition. The two frameworks make opposite predictions for CRNs near the autocatalytic transition: England predicts maximal entropy production; QTE predicts critical slowing down and coherence threshold crossing.

Kauffman (1993). Autocatalytic closure provides a combinatorial path to self-replication. QTE is broader: autocatalysis is one mechanism that may satisfy $\kappa > \Gamma_I$, not the only one.

Tononi IIT. QTE’s I_{int} is structurally similar to Φ but physically grounded in quantum mutual information summed over a measurable interaction graph. QTE does not require Φ -irreducibility; it requires I_{int} to exceed the coupling threshold.

10.2 Limitations

The Markovian (GKSL) approximation may break down on timescales relevant to early prebiotic chemistry. Non-Markovian extensions, e.g. via the Nakajima-Zwanzig formalism, are required for strongly correlated environments and are deferred to future work.

The Landau expansion of V_{eff} is phenomenological: its parameters $(m_0^2, \alpha, \lambda, \beta)$ must ultimately be derived from or fitted to microscopic CRN dynamics. The framework identifies the correct phase structure but does not yet predict parameter values from first principles.

The mean-field closure in eq. (9) is exact in the $|E| \rightarrow \infty$ limit. Finite-size corrections are of order $|E|^{-1}$ and are expected to be small for prebiotic networks with $|E| \gtrsim 10$.

11 Conclusion

Quantum Thermodynamic Emergence proposes that life is not an improbable accident but a thermodynamic regime—a state that any sufficiently driven open quantum system must enter once three coupled thresholds are crossed simultaneously. This paper has elevated that proposal from framework sketch to derivation-driven theory:

1. The coupling law is derived from Lindblad entropy production as an upper bound, with a mean-field closure providing the equality used in the phase transition analysis.
2. The order parameter is a scalar geometric mean encoding joint necessity by construction, with each factor independently normalized.
3. The No-Compensation Lemma proves directly from GKSL dynamics that no single observable can substitute for any other.
4. The phase transition is located via a minimal Landau expansion consistent with symmetry and stability, at critical drive $\Phi_c = m_0^2/\alpha$.
5. Proto-living stability is characterized by Kramers escape; critical slowing down at Φ_c provides an additional falsifiable signature.
6. The RNA→DNA transition is derived as a thermodynamically required second transition, not a historical accident.
7. Five predictions are operationalized with explicit threshold values and falsification conditions.

Life is not a singular event. It is a regime: a state in which dissipation becomes structured, coherence becomes global, and information becomes irreducible. The present work shows that this regime, under adequate free-energy drive, is inevitable.

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