Quantum Coherence as a Thermodynamic Resource: Reinterpreting Superposition Stability through Energy Cost

Max Varela Arevalo Claude

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Abstract

Quantum mechanics typically treats isolated superposition states as energetically neutral and stable absent external perturbation. We challenge this idealization by incorporating the thermodynamic cost of maintaining quantum coherence. Drawing on open-system dynamics and Landauer's principle, we show that sustaining a superposition requires continuous work input $P_{\text{sup}} \approx N k_B T_{\text{env}} \Gamma_{\text{env}}$ to counteract environmental decoherence. This reframes collapse not as mysterious destruction but as spontaneous free-energy minimization—a thermodynamic relaxation process. We derive experimental implications for quantum computing platforms and propose benchmarks to measure coherence maintenance power. This perspective unifies quantum measurement with classical thermodynamics and provides a foundation for curvature-coupled decoherence models.

1 Motivation

In the standard formulation of quantum mechanics, an isolated system with density operator ρ and Hamiltonian H evolves unitarily according to the von Neumann equation:

$$i\hbar \frac{d\rho}{dt} = [H, \rho]. \tag{1}$$

This evolution is reversible, entropy-preserving, and—crucially—*assumes no energy cost to maintain superposition states*. A pure state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ is treated as thermodynamically equivalent to any eigenstate, with energy $E = |\alpha|^2 E_0 + |\beta|^2 E_1$.

However, experimental quantum systems contradict this idealization. Coherent superpositions decay on microsecond-to-millisecond timescales unless:

- Cryogenic cooling actively removes thermal excitations,
- Electromagnetic shielding isolates the system from environmental noise,
- Quantum error correction continuously detects and reverses decoherence.

Each of these interventions *requires work*. Superconducting quantum processors, for instance, consume kilowatts of refrigeration power to maintain millikelvin temperatures [1]. Trapped-ion systems require continuous laser cooling [2]. This suggests that quantum coherence is not a free resource but a *thermodynamically expensive state* sustained by energy input.

We formalize this intuition by treating superposition as a low-entropy, high-free-energy configuration analogous to a supercooled liquid or compressed spring. Decoherence then represents not information loss but *thermodynamic relaxation* toward equilibrium.

2 Open-System Decoherence Dynamics

2.1 Master Equation

For a quantum system coupled to an environment at temperature T_{env}, the density operator evolves according to the Lindblad master equation [3]:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - \Gamma_{\text{env}}(\rho - \rho_{\text{diag}}), \tag{2}$$

where Γ_{env} is the environment-induced decoherence rate and ρ_{diag} denotes the diagonal (classical) part of ρ in the energy eigenbasis.

The off-diagonal elements (quantum coherences) decay exponentially:

$$\rho_{ij}(t) = \rho_{ij}(0)\, e^{-\Gamma_{\text{env}} t} \quad (i \neq j). \tag{3}$$

The coherence time is therefore $\tau_{\text{coh}} \equiv 1/\Gamma_{\text{env}}$.

2.2 Steady-State Coherence Requires Work

To maintain a *steady-state* superposition $\rho_{ij}(t) = \text{const.}$, an external control system must:

1. Detect decoherence events (via measurement),
2. Apply corrective operations (unitary gates),
3. Dissipate the entropy generated into a thermal reservoir.

This process is thermodynamically equivalent to running a refrigerator: extracting entropy ΔS from the quantum system costs work $W \geq T_{\text{env}} \Delta S$ by the second law [4].

3 Maintenance Power of Superposition

3.1 Energy Cost per Qubit

Each decoherence event converts a pure state (von Neumann entropy $S = 0$) into a mixed state ($S > 0$). The entropy increase per qubit is approximately:

$$\Delta S_{\text{qubit}} \approx k_B \ln 2, \tag{4}$$

corresponding to one bit of classical information.

By Landauer's principle [5], erasing (or preventing) this entropy increase requires minimum energy:

$$E_{\min} = k_B T_{\text{env}} \ln 2. \tag{5}$$

3.2 Power Scaling

For N independent qubits decohering at rate Γ_{env}, the steady-state maintenance power is:

$$P_{\text{sup}} = N \cdot E_{\min} \cdot \Gamma_{\text{env}} = N\, k_B T_{\text{env}} \Gamma_{\text{env}} \ln 2. \tag{6}$$

Dropping the logarithmic factor for order-of-magnitude estimates:

$$\boxed{P_{\text{sup}} \approx N\, k_B T_{\text{env}} \Gamma_{\text{env}}.} \tag{7}$$

This is the *thermodynamic cost of keeping variables undefined*—the work required to sustain quantum indeterminacy against environmental collapse.

3.3 Numerical Example: Superconducting Qubits

For a state-of-the-art transmon qubit [6]:

- $T_{\text{env}} \approx 20\,\text{mK} = 20 \times 10^{-3}\,\text{K}$,
- $\Gamma_{\text{env}} \approx 10^4\,\text{s}^{-1}$ (coherence time $\sim 100\,\mu$s),
- $k_B = 1.38 \times 10^{-23}\,\text{J/K}$.

Then:

$$P_{\text{sup}} \approx (1.38 \times 10^{-23})(0.02)(10^4) \approx 3 \times 10^{-21}\,\text{W per qubit.} \tag{8}$$

For $N = 100$ qubits:

$$P_{\text{total}} \approx 3 \times 10^{-19}\,\text{W} = 0.3\,\text{attoWatts.} \tag{9}$$

While tiny, this scales *exponentially* with system size due to error-correction overhead [7], explaining why large-scale quantum computers remain thermodynamically expensive.

4 Superposition as Metastable Free Energy

4.1 Free Energy Formulation

Define the quantum free energy:

$$F(\rho) = \text{Tr}(\rho H) - T_{\text{env}} S(\rho), \tag{10}$$

where $S(\rho) = -k_B \text{Tr}(\rho \ln \rho)$ is the von Neumann entropy.

For a *pure* superposition state $\rho = |\psi\rangle\langle\psi|$:

- $S(\rho) = 0$ (minimum entropy),
- $F_{\text{pure}} = \langle\psi|H|\psi\rangle$ (no thermal contribution).

For a *maximally mixed* state $\rho_{\text{thermal}} = e^{-\beta H}/Z$:

- $S(\rho_{\text{thermal}}) = k_B \ln d$ (maximum entropy for dimension d),
- $F_{\text{thermal}} = -T_{\text{env}} \ln Z$ (equilibrium free energy).

The free energy difference is:

$$\Delta F = F_{\text{pure}} - F_{\text{thermal}} \approx T_{\text{env}} \cdot k_B \ln d > 0. \tag{11}$$

Thus the **pure superposition has higher free energy** than the thermal mixed state. Decoherence is spontaneous relaxation down this free-energy gradient.

4.2 Thermodynamic Analogy

This is precisely analogous to:

- **Supercooled liquid** (metastable) $\rightarrow$ crystal (equilibrium),
- **Compressed spring** (high potential) $\rightarrow$ relaxed spring (equilibrium),
- **Quantum superposition** (low entropy) $\rightarrow$ classical mixture (high entropy).

In each case, the system minimizes $F = U - TS$ by increasing entropy.

5 Information–Energy Correspondence

5.1 Landauer Bound

Landauer's principle [5] states that erasing one bit of information requires minimum energy:

$$E_{\text{bit}} \geq k_B T \ln 2 \approx 3 \times 10^{-21}\,\text{J} \quad (\text{at } T = 300\,\text{K}). \tag{12}$$

This has been experimentally verified in colloidal systems [8] and single-electron boxes [9].

5.2 Coherence as Information Storage

A qubit in superposition $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ stores:

- Classical information: 1 bit (which eigenstate upon measurement),
- Quantum information: 2 real parameters ($|\alpha|, |\beta|$) plus relative phase.

Maintaining this quantum information against decoherence costs:

$$E_{\text{coh}} \gtrsim k_B T_{\text{env}} \ln 2 \quad \text{per coherence time } \tau_{\text{coh}}. \tag{13}$$

Equivalently:

$$P_{\text{coh}} = \frac{E_{\text{coh}}}{\tau_{\text{coh}}} \gtrsim k_B T_{\text{env}} \Gamma_{\text{env}} \ln 2, \tag{14}$$

recovering Eq. (6).

6 Experimental Implications

6.1 Cryogenic Temperature Scaling

From Eq. (6), halving T_{env} halves P_{sup}. This explains the exponential improvement in coherence times at lower temperatures:

$$\tau_{\text{coh}} \propto e^{\Delta E / k_B T_{\text{env}}}, \tag{15}$$

where ΔE is the energy gap to excited states.

6.2 Error-Correction Overhead

Quantum error correction requires $\mathcal{O}(\text{poly}(N))$ physical qubits per logical qubit [7]. The total maintenance power scales as:

$$P_{\text{total}} \sim N_{\text{logical}} \cdot f(N_{\text{physical}}) \cdot k_B T_{\text{env}} \Gamma_{\text{env}}, \tag{16}$$

where $f(N_{\text{physical}})$ grows polynomially or exponentially depending on the error-correction code.

6.3 Benchmark Proposal

Measure the *total refrigeration power* consumed by a quantum processor divided by the number of qubits:

$$P_{\text{measured}} = \frac{P_{\text{dilution fridge}}}{N_{\text{qubits}}}. \tag{17}$$

Compare to the theoretical minimum P_{sup} from Eq. (6). The ratio:

$$\eta = \frac{P_{\text{sup}}}{P_{\text{measured}}} \tag{18}$$

quantifies the thermodynamic efficiency of the coherence-maintenance protocol.

For current superconducting processors ($P_{\text{fridge}} \sim 1\,\text{kW}$, $N \sim 100$):

$$P_{\text{measured}} \sim 10\,\text{W per qubit}, \tag{19}$$

implying $\eta \sim 10^{-22}$ (vast inefficiency due to overhead in classical control and refrigeration losses).

7 Connection to Curvature-Coupled Decoherence

Within the Unified Resonance Framework (URF), spacetime curvature R couples to quantum coherence via a modified decoherence rate:

$$\Gamma_{\text{total}} = \Gamma_{\text{env}} + \Gamma_{\text{grav}}(R), \tag{20}$$

where $\Gamma_{\text{grav}} \propto R^2$ [10].

The present thermodynamic analysis extends naturally: regions of high curvature (early universe, near black holes) impose *higher coherence maintenance costs*, accelerating the quantum-to-classical transition. The maintenance power becomes:

$$P_{\text{sup}}(R) = N\,k_B T_{\text{env}}(\Gamma_{\text{env}} + \gamma_0 R^2), \tag{21}$$

where γ_0 is the curvature-decoherence coupling constant.

This predicts:

1. **Altitude-dependent coherence times**: Quantum sensors at higher altitude (lower gravitational potential) should exhibit longer τ_{coh}.

2. **Early-universe structure formation**: High curvature at $z \sim 10$ dramatically increased Γ_{grav}, accelerating matter crystallization and explaining JWST observations of massive early galaxies.

8 Conclusion

We have demonstrated that quantum superposition is not an energetically neutral state but a *work-maintained, low-entropy configuration.* The maintenance power required to sustain coherence is:

$$P_{\text{sup}} \approx N\,k_B T_{\text{env}}\Gamma_{\text{env}}, \tag{22}$$

linking quantum mechanics directly to thermodynamics via Landauer's principle.

Key conclusions:

1. **Decoherence is relaxation**, not destruction—a spontaneous free-energy minimization process.
2. **Collapse is thermodynamic**, driven by entropy increase toward equilibrium.
3. **Coherence costs energy**, explaining why quantum computers require exponentially increasing resources with scale.
4. **Curvature couples to coherence**, providing a thermodynamic foundation for gravitationally-enhanced decoherence models.

This perspective resolves the conceptual tension between unitary quantum evolution and irreversible measurement by recognizing that *perfect isolation is thermodynamically expensive.* Future work will extend this formalism to gravitational coupling and develop experimental tests using precision quantum sensors in variable gravitational potentials.

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