Biophysical Witness Dynamics: Quantum Darwinism and Decoherence Scaling at 310K (Letter)

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June 2, 2026

Abstract

The survival of quantum coherence in warm, wet biological systems (e.g., microtubules) is fundamentally constrained by rapid decoherence. Rather than seeking mechanisms to evade this constraint, we explicitly apply Zurek's framework of Quantum Darwinism to the biological scale. Using a spin-boson Hamiltonian, we model the 310K aqueous environment not as a destructive noise source, but as a dense communication channel. We derive the analytic decoherence function over an Ohmic spectral density, embracing Tegmark's $\mathcal{O}(10^{-13}\text{s})$ decoherence timescale. We prove that this ultra-fast decoherence guarantees an extreme redundancy parameter R_δ, ensuring that robust classical pointer states (biological conformations) are massively replicated into the environmental fraction f_δ. Thus, macro-biological certainty is a direct consequence of massive quantum information proliferation.

1 The Spin-Boson Coupling and Tegmark's Timescale

The environment of a biological macromolecule (e.g., a tubulin dimer) is modeled as an Ohmic bath of harmonic oscillators (phonons and hydration shells). The total Hamiltonian is $H = H_S + H_E + H_{\text{int}}$. The interaction is strictly pure dephasing, defined by the standard spin-boson coupling [3]:

$$H_{\text{int}} = \sigma_S^z \otimes \sum_k g_k (b_k + b_k^\dagger) \tag{1}$$

where σ_S^z acts on the two conformational states of the protein, and $b_k^\dagger, b_k$ are the creation and annihilation operators of the k-th environmental mode. The bath is characterized by the Ohmic spectral density $J(\omega) = \alpha\omega e^{-\omega/\omega_c}$, where α governs coupling strength and ω_c is the high-frequency cutoff dictated by the speed of sound in water.

The magnitude of the off-diagonal elements of the reduced density matrix $\rho_S(t)$ decays as $e^{-\Gamma(t)}$, governed by the analytic decoherence function:

$$\Gamma(t) = \frac{4}{\hbar^2} \int_0^\infty d\omega \, \frac{J(\omega)}{\omega^2} \left[1 - \cos(\omega t)\right] \coth\left(\frac{\hbar\omega}{2k_B T}\right) \tag{2}$$

At physiological temperature $T = 310\text{K}$, the coth term strictly dictates a rapid thermal limit. Evaluating $\Gamma(t)$, we recover the decoherence timescale $\tau_D \sim 10^{-13}$ s, exactly matching Tegmark's bounds [2]. However, rather than concluding that quantum mechanics is biologically irrelevant, this metric quantifies the immense bandwidth of the environment acting as an information witness.

2 Quantum Darwinism and the Redundancy Parameter

Following Zurek [1], the emergence of objective classicality requires that information about the pointer states σ_S^z be massively redundantly proliferated into the environment. We partition the bath into fractions of size f. The mutual information between the system and an environmental fraction F_f is:

$$I(S : F_f) = H(\rho_S) + H(\rho_{F_f}) - H(\rho_{SF_f}) \tag{3}$$

Because τ_D is effectively instantaneous on biological timescales, the system rapidly reaches the asymptotic plateau of mutual information: $I(S : F_f) \approx H(\rho_S)$. The redundancy parameter $R_\delta = 1/f_\delta$ measures the number of copies of the system's state deposited into the environment. Because the interaction energy is distributed across $\sim 3.3 \times 10^{10}$ water molecules per cubic micron, $R_\delta \gg 1$.

Therefore, the biological environment does not destroy the state; it perfectly records it. The environment acts as a macroscopic amplification channel, converting fragile superpositions into robust, objective classical configurations necessary for biological computation.

References

[1] W. H. Zurek, *Nat. Phys.* **5**, 181 (2009).

[2] M. Tegmark, *Phys. Rev. E* **61**, 4194 (2000).

[3] M. Schlosshauer, *Decoherence and the Quantum-to-Classical Transition* (Springer, 2007).