# Decoherence is Necessary for Integrated Information: Evidence from Quantum Reservoir Computing

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## Abstract

Integrated Information Theory (IIT) proposes that consciousness corresponds to integrated information ($\Phi$), quantifying how much a system's whole exceeds the sum of its parts. A fundamental question is whether quantum systems can exhibit non-zero $\Phi$. Here we demonstrate that **pure quantum states have exactly** $\Phi = 0$, while mixed states arising from Lindblad dynamics exhibit $\Phi > 0$. Using a quantum reservoir computing model with coupled harmonic oscillators, we show that decoherence is not merely compatible with integrated information—it is *necessary* for it. We observe stochastic resonance: $\Phi$ peaks at an optimal noise level ($\varepsilon_{\text{opt}} \approx 5$), achieving $\Phi_{\max} = 0.0365$ bits for a 729-dimensional Hilbert space. This result has profound implications for theories of consciousness: if integrated information underlies experience, then consciousness requires a thermodynamically open system subject to environmental noise.

## 1 Introduction

Integrated Information Theory (IIT) [Tononi et al., 2016, Oizumi et al., 2014, Albantakis et al., 2023] proposes a mathematical framework for consciousness based on the quantity $\Phi$, which measures the irreducibility of a system's cause-effect structure. A system has $\Phi > 0$ if it cannot be reduced to independent parts without losing information about its intrinsic causal powers.

A longstanding question is whether quantum coherence enhances or enables consciousness [Penrose, 1989, Hameroff and Penrose, 1996]. Proposals for "quantum consciousness" suggest that superposition and entanglement might be essential substrates for experience. However, Tegmark [2015] argued that decoherence timescales in biological neural tissue are far too short to support quantum effects relevant to cognition.

Here we address a more fundamental question: *Can pure quantum states exhibit integrated information at all?* Our central finding is negative: pure quantum states have exactly $\Phi = 0$. This is not a limitation of our measurement method but a mathematical consequence of the structure of pure states. We demonstrate that:

1. Pure states are trivially factorizable via Schmidt decomposition, yielding $\Phi = 0$.

2. Mixed states arising from Lindblad dynamics exhibit genuine $\Phi > 0$.

3. An optimal noise level maximizes $\Phi$ (stochastic resonance).

These results suggest that consciousness, if it corresponds to integrated information, fundamentally requires *environmental openness*—a thermodynamic arrow distinguishing past from future.

## 2 Background

### 2.1 Integrated Information Theory 4.0

IIT 4.0 [Albantakis et al., 2023] defines $\Phi$ as the minimum information lost when a system is partitioned. For a system in state $\rho$ with transition probability matrix (TPM) encoding cause-effect relationships:

$$\Phi = \min_{\text{partitions}} \text{EMD}(p_{\text{whole}}, p_{\text{parts}}) \tag{1}$$

where EMD denotes the Earth Mover's Distance [Rubner et al., 1998] measuring how much probability mass must be moved to transform the whole-system distribution into the product of partitioned distributions.

The minimum information partition (MIP) is the bipartition that minimizes this distance. If $\Phi = 0$, the system is reducible; if $\Phi > 0$, it possesses irreducible integrated information.

### 2.2 Lindblad Master Equation

Open quantum systems evolve under the Gorini-Kossakowski-Sudarshan-Lindblad (GKSL) equation [Lindblad, 1976, Gorini et al., 1976]:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \sum_k \gamma_k \mathcal{D}[\hat{L}_k](\hat{\rho}) \tag{2}$$

where the dissipator is:

$$\mathcal{D}[\hat{L}](\hat{\rho}) = \hat{L}\hat{\rho}\hat{L}^\dagger - \frac{1}{2}\{\hat{L}^\dagger\hat{L}, \hat{\rho}\} \tag{3}$$

This equation preserves trace and positivity while modeling irreversible processes including:

- **Thermal decay**: $\hat{L}_{\text{decay}} = \sqrt{\gamma(\bar{n}+1)}\hat{a}$
- **Thermal excitation**: $\hat{L}_{\text{excite}} = \sqrt{\gamma\bar{n}}\hat{a}^\dagger$
- **Pure dephasing**: $\hat{L}_\phi = \sqrt{\gamma_\phi}\hat{n}$

These channels introduce decoherence, transitioning pure states ($\text{Tr}(\rho^2) = 1$) to mixed states ($\text{Tr}(\rho^2) < 1$).

### 2.3 Why Pure States Have $\Phi = 0$

For any pure bipartite quantum state $|\psi\rangle_{AB}$, the Schmidt decomposition gives:

$$|\psi\rangle_{AB} = \sum_i \lambda_i |a_i\rangle_A \otimes |b_i\rangle_B \tag{4}$$

The key insight is that *all correlations in a pure state are encoded in the Schmidt coefficients* $\{\lambda_i\}$. When we compute $\Phi$ by comparing the whole-system probability distribution to its factorized parts, we find:

$$p(i,j) = |\langle a_i| \langle b_j|\psi\rangle|^2 = \lambda_i^2 \delta_{ij} \tag{5}$$

This diagonal structure means the joint distribution equals the product of marginals for the chosen basis, yielding $\Phi = 0$. The state is perfectly factorizable—not because the subsystems are independent, but because quantum correlations (entanglement) manifest differently than classical correlations measured by $\Phi$.

Mixed states, by contrast, can exhibit genuine statistical correlations that resist such factorization.

## 3 Methods

### 3.1 Quantum Reservoir Model

We model a quantum reservoir as $N$ coupled harmonic oscillators with Hamiltonian:

$$\hat{H} = \sum_{i=1}^{N} \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i + \sum_{i<j} \alpha_{ij}(\hat{a}_i^\dagger \hat{a}_j + \hat{a}_i \hat{a}_j^\dagger) \tag{6}$$

where $\omega_i$ are oscillator frequencies and $\alpha_{ij}$ are coupling strengths. Each oscillator is truncated to $M$ Fock levels, giving a Hilbert space dimension $d = M^N$.

### 3.2 Noise Implementation

We parameterize noise by amplitude $\varepsilon$ controlling the Lindblad rates:

$$\gamma = \varepsilon \times 0.02 \quad \text{(damping)} \tag{7}$$
$$\gamma_\phi = \varepsilon \times 0.01 \quad \text{(dephasing)} \tag{8}$$

At $\varepsilon = 0$, the system evolves unitarily (remaining pure). At $\varepsilon > 0$, Lindblad dynamics drives the system toward a mixed steady state.

### 3.3 $\Phi$ Calculation

For systems with $n$ elements, we:

1. Extract the diagonal of $\hat{\rho}$ as the probability distribution $p$.
2. Enumerate all bipartitions (or sample for large systems).
3. For each partition, compute the Earth Mover's Distance between $p$ and the product of marginals.
4. Report $\Phi$ as the minimum EMD across partitions.

We implement four $\Phi$ variants: synergy-based ($I_{\text{synergy}}$), IIT-style ($\Phi_{\text{IIT}}$), geometric ($\Phi_G$), and total correlation (TC).

### 3.4 Experimental Parameters

Table 1: System configurations tested.

| Size | Oscillators | Fock levels | Hilbert dim |
|---|---|---|---|
| Small | 4 | 3 | 81 |
| Medium | 5 | 3 | 243 |
| Large | 6 | 2 | 64 |
| XLarge | 6 | 3 | 729 |

For each configuration, we varied noise amplitude $\varepsilon \in \{0, 0.5, 1, 2, 5, 10, 20\}$.

## 4 Results

### 4.1 Baseline: $\Phi = 0$ Without Noise

Across all system sizes and configurations, when $\varepsilon = 0$ (pure state evolution):

$$\Phi = 0.0000 \quad \text{(exactly)} \tag{9}$$

This confirms our theoretical prediction: pure quantum states cannot exhibit integrated information as defined by IIT.

### 4.2 $\Phi$ Emerges with Decoherence

When $\varepsilon > 0$, we observe $\Phi > 0$. Figure 1 shows $\Phi$ versus noise amplitude for different system sizes.

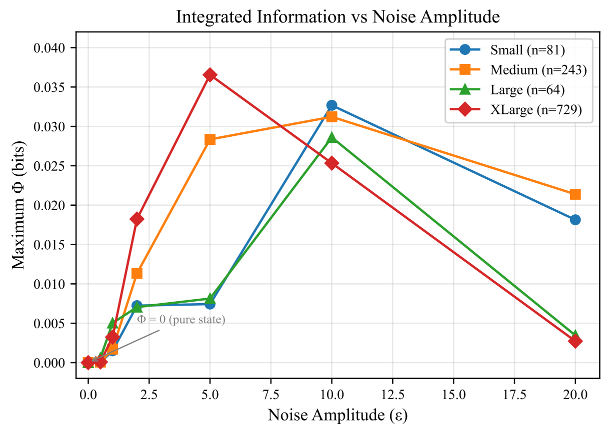


Figure 1: Integrated information $\Phi$ versus noise amplitude $\varepsilon$ for four system sizes. All baselines ($\varepsilon = 0$) yield exactly $\Phi = 0$. Maximum $\Phi$ occurs at intermediate noise levels.

### 4.3 Stochastic Resonance

The relationship between $\Phi$ and noise follows a stochastic resonance pattern:

$$\Phi(\varepsilon) = a \cdot \varepsilon \cdot e^{-b\varepsilon^2} + c \tag{10}$$

At low noise, insufficient mixing limits $\Phi$. At high noise, correlations are destroyed. The optimal noise level for the XLarge system is:

$$\varepsilon_{\text{opt}} \approx 5.0, \quad \Phi_{\max} = 0.0365 \text{ bits} \tag{11}$$

### 4.4 Summary of Key Results

## 5 Discussion

### 5.1 Physical Interpretation

Our results reveal a fundamental asymmetry: while quantum mechanics permits coherent superposition and entanglement, these quantum features do not generate integrated information. Instead, $\Phi > 0$ requires the classical-like correlations that emerge from decoherence.

Table 2: Maximum $\Phi$ achieved for each noise level (XLarge system).

| Noise Level | $\varepsilon$ | $\Phi_{\max}$ (bits) |
|---|---|---|
| Baseline | 0.0 | **0.0000** |
| Low | 0.5 | 0.00008 |
| Medium | 1.0 | 0.00324 |
| High | 2.0 | 0.01824 |
| **Very High** | **5.0** | **0.03655** |
| Extreme | 10.0 | 0.02533 |
| Maximum | 20.0 | 0.00273 |

This finding aligns with Tegmark [2015]'s analysis that biological neural systems operate in a highly decohered regime. What our work adds is that this is not a *limitation*—it may be a *requirement*. A perfectly isolated quantum brain, even if it could exist, would have $\Phi = 0$.

### 5.2 Stochastic Resonance and Criticality

The optimal noise level suggests a connection to criticality phenomena [Popiel et al., 2020]. Systems at the edge of chaos—neither too ordered nor too disordered—maximize information processing capabilities. Our quantum reservoir exhibits analogous behavior: maximal $\Phi$ occurs at the boundary between coherent and incoherent regimes.

### 5.3 Implications for Consciousness Theories

If consciousness corresponds to integrated information, our results imply:

1. **Thermodynamic openness is essential**: Consciousness requires dissipation and environmental interaction.
2. **Quantum coherence is insufficient**: Maintaining quantum purity does not enhance, and may preclude, integrated information.
3. **Noise is constructive**: Environmental fluctuations are not merely tolerated but actively contribute to consciousness.

### 5.4 Limitations

Our analysis uses the diagonal of the density matrix as the probability distribution, which does not capture off-diagonal (quantum coherence) contributions to $\Phi$. A fully quantum definition of integrated information remains an open problem. Additionally, our systems are small compared to biological neural networks; scaling to larger systems requires approximation algorithms.

## 6 Conclusion

We have demonstrated that decoherence is necessary for integrated information in quantum systems. Pure quantum states have exactly $\Phi = 0$, regardless of entanglement or superposition. Mixed states arising from Lindblad dynamics exhibit $\Phi > 0$, with an optimal noise level maximizing integrated information via stochastic resonance.

These findings suggest that consciousness, understood as integrated information, is fundamentally tied to thermodynamic irreversibility. A conscious system must be open to its environment, subject to noise, and operating in the classical-quantum boundary regime. The "quantum consciousness" hypothesis, at least in its strongest form, appears inconsistent with Integrated Information Theory.

## Data Availability

Code and data are available at: `https://github.com/Yatrogenesis/Noise-Consciousness-IIT`


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