Quantum Decoherence:
Coherence Diffusion into a Noise Black Hole

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Abstract

Quantum decoherence is traditionally modeled through empirical decay laws in which observable coherence decreases with time. While these models successfully describe the dynamics of open quantum systems, they do not by themselves explain the physical destination of the apparently lost coherence. Motivated by the Structured Quantum Noise (SQN) framework, which models noise as a structured quantum subsystem rather than a scalar attenuation parameter, this paper proposes an information-theoretic interpretation of decoherence as coherence redistribution into environmental degrees of freedom. We introduce the concept of a *Noise Black Hole*, a hierarchical environmental structure through which coherence and entanglement diffuse into progressively less accessible sectors while remaining globally conserved. A minimal coherence-retention model shows that the familiar exponential decoherence law emerges naturally from repeated information redistribution rather than being imposed phenomenologically. The framework further predicts that deviations from ideal exponential decay arise from differences in environmental structure, memory, coupling, and backflow pathways, suggesting that measured decoherence curves may provide indirect probes of otherwise inaccessible environmental Hilbert-space dynamics. Rather than modifying conventional open-system theory, the proposed framework provides a possible information-theoretic explanation for the observed form of decoherence while generating experimentally testable predictions.

1 Introduction

Quantum decoherence is central to quantum mechanics, quantum information theory, quantum metrology, and quantum technology. The standard open-system description represents the observed subsystem by a reduced density matrix and often models coherence decay through an empirical exponential law,

$$C(t) = C_0 e^{-\gamma t}. \tag{1}$$

Such decay laws appear throughout open quantum systems, including dephasing, relaxation, Ramsey decay, and loss of interference visibility [1–4].

Equation (1) is experimentally useful, but it leaves a conceptual question unanswered:

Where does the coherence go?

If the combined system and environment evolve unitarily, quantum information should not disappear. Observable coherence may diminish, but the underlying information must remain encoded somewhere in the joint system-environment state. Decoherence therefore need not be interpreted as information destruction. It may instead be interpreted as information-theoretic redistribution.

Recent work on Structured Quantum Noise proposed that noise should be modeled as a structured quantum subsystem with its own degrees of freedom, memory, and interaction pathways [5]. In that framework, coherence, negativity, and quantum Fisher information can leave an observed subsystem, reside temporarily in environmental degrees of freedom, and later return through coherent pathway interference. The existence of such revival is evidence that apparent decoherence can represent redistribution rather than destruction.

The present paper investigates a direct consequence of that viewpoint. If coherence can migrate into environmental degrees of freedom, then repeated migration into progressively deeper environmental sectors should produce an effective decay law. We show that a minimal coherence-retention model naturally produces exponential decoherence. The result should be understood as a prediction of the structured-noise perspective: the generic shape of decoherence can emerge from coherence diffusion into a large environmental Hilbert space.

Unlike conventional phenomenological models, the proposed framework seeks to explain the physical origin of the observed decoherence law while preserving the standard mathematical formalism of open quantum systems.

2 Structured Quantum Noise and Information Redistribution

The Structured Quantum Noise framework begins with a simple premise:

Noise is itself a quantum system.

Consequently, an environmental subsystem may possess quantum states, memory, dynamics, coherence capacity, entanglement capacity, and information capacity. Let AB denote an observed subsystem and let N denote an environmental degree of freedom. The joint state evolves as

$$\rho_{ABN}(t) = U(t)\rho_{ABN}(0)U^{\dagger}(t). \tag{2}$$

The observed state is obtained by tracing out N:

$$\rho_{AB}(t) = \mathrm{Tr}_N\left[\rho_{ABN}(t)\right]. \tag{3}$$

Equations (2) and (3) express the central distinction. Globally, information is preserved by unitary evolution. Locally, information appears lost because the observer has access only to a reduced subsystem. The reduced-system loss is therefore compatible with global information conservation [6, 7].

In the Structured Quantum Noise model, coherence does not merely attenuate. It can migrate between observed and environmental sectors. A minimal pathway picture is

$$AB \longrightarrow AN \longrightarrow BN \longrightarrow AB, \tag{4}$$

where coherence and entanglement can leave AB, become stored in correlations involving N, and later re-enter the observed sector. Such behavior motivates the broader hypothesis of the present paper:

> Decoherence is an information-theoretic redistribution phenomenon rather than an information-destruction phenomenon.

3 Noise Black Hole

3.1 Coherence Diffusion into a Noise Black Hole

We now extend the single-memory picture to a hierarchy of environmental memory subsystems

$$N_1, N_2, N_3, \ldots . \tag{5}$$

Instead of assuming that coherence is destroyed when it leaves the observed subsystem, we represent its dominant location through an information chain,

$$E_0 \leftrightarrow E_1 \leftrightarrow E_2 \leftrightarrow E_3 \leftrightarrow \cdots , \tag{6}$$

with

$$E_0 = AB, \tag{7}$$
$$E_1 = AN_1, \tag{8}$$
$$E_2 = N_1N_2, \tag{9}$$
$$E_3 = N_2N_3, \tag{10}$$

and so on.

In this representation, coherence and entanglement do not behave like classical particles. Rather, the chain labels where the relevant information is predominantly encoded. The migration process may be written schematically as

$$AB \leftrightarrow AN_1 \leftrightarrow N_1N_2 \leftrightarrow N_2N_3 \leftrightarrow \cdots . \tag{11}$$

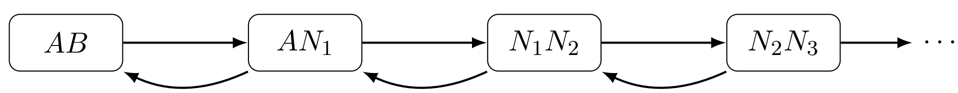

Figure 1: Noise Black Hole model. Coherence and entanglement migrate through progressively deeper environmental sectors. The chain denotes dominant information location, not a classical splitting of coherence into independent fragments.

This chain captures the intuition that coherence may drift away from the observable sector into progressively deeper environmental sectors. At every level there may be both forward-flow pathways and backflow pathways. The observed decay is controlled not by a single microscopic path, but by the net fraction of coherence that remains reconstructible in the observed subsystem after each redistribution stage.

We refer to the environmental hierarchy in Eq. (11) as a *Noise Black Hole*. The terminology does not imply information destruction. It reflects increasing information inaccessibility. Coherence remains present globally, but it becomes distributed among environmental degrees of freedom in a way that is progressively harder to reconstruct from the observed subsystem alone.

3.2 Coherence Retention in Diffusion

The probability picture is useful for motivating the retention model. Suppose coherence has reached a redistribution stage in the environmental hierarchy. At the next stage there are two effective possibilities: coherence may flow deeper into the Noise Black Hole, or it may remain reconstructible from the observed subsystem through retention, backflow, or coherent recurrence. This picture qualitatively resembles discussions of information accessibility in gravitational black holes. In particular, coherence backflow may be viewed as analogous to Hawking radiation in the limited sense that information remains recoverable through retention and backflow pathways while coherence simultaneously continues to diffuse into deeper environmental sectors. The analogy is intended only to provide physical intuition and should not be interpreted as a claim of physical equivalence.

Let p denote the effective probability of forward flow into deeper environmental sectors. Then $1 - p$ denotes the effective probability of retained or backflow-accessible coherence.

This probability language should be interpreted carefully. Coherence and entanglement are not assumed to split into independent classical pieces. If entanglement were literally fragmented into independent parts, the original entanglement structure would be destroyed. Instead, the underlying quantum state evolves unitarily through available interaction pathways. The probabilities introduced here are observer-level effective quantities describing whether coherence remains reconstructible from the reduced subsystem after a redistribution stage.

Define

$$r = 1 - p, \tag{12}$$

where $0 < r < 1$ is the effective coherence-retention factor. More generally, r represents the net fraction of coherence that remains accessible to the observed subsystem after one redistribution stage. It may include direct retention, partial backflow, constructive interference, destructive interference, and unresolved environmental structure.

The minimal retention model is

$$C_{n+1} = rC_n. \tag{13}$$

Iterating Eq. (13) gives

$$C_n = r^n C_0. \tag{14}$$

Writing

$$\gamma = -\ln r, \tag{15}$$

we obtain

$$C_n = C_0 e^{-\gamma n}. \tag{16}$$

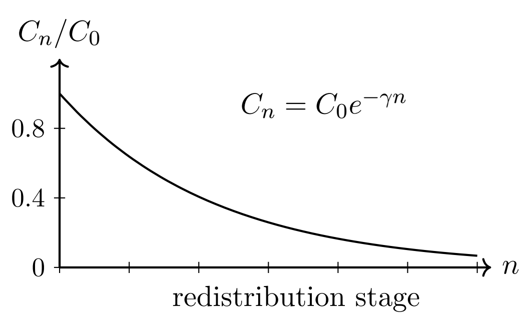

Figure 2: Generic exponential decoherence predicted by the minimal coherence-retention model. The curve represents leading-order observable coherence decay when the effective retention factor is approximately constant across redistribution stages.

Equation (16) has the same form as the familiar exponential decoherence law. The exponential was not assumed as a primitive phenomenological rule. It emerged from repeated information-theoretic redistribution with a fixed effective retention factor.

If p is defined as the probability of forward flow into the Noise Black Hole, then Eq. (12) gives

$$\gamma = -\ln(1-p). \tag{17}$$

If p is instead defined as the probability of backflow or retained coherence, then $r = p$ and

$$\gamma = -\ln p. \tag{18}$$

Thus the sign of the decay does not depend on which probability convention is used. The physical quantity controlling the observed decay is the net retention factor r.

The prediction of the minimal model is not that every decoherence experiment must follow an identical exponential curve. Rather, the prediction is that coherence diffusion into environmental degrees of freedom naturally produces the generic exponential shape of decoherence as a leading-order behavior. Different noise environments may contain different modalities, coupling strengths, memory depths, pathway topologies, and backflow mechanisms. Therefore the retention factor may vary with stage:

$$C_n = C_0 \prod_{k=1}^{n} r_k. \tag{19}$$

When $r_k = r$ is constant, Eq. (19) reduces to the pure exponential law in Eq. (16). When r_k varies, deviations from a pure exponential are expected.

This provides a direct experimental prediction of the Noise Black Hole interpretation: different environmental structures should produce different retention-factor sequences r_k, so departures from ideal exponential decay may encode measurable information about environmental topology, memory depth, modality, coupling heterogeneity, and backflow pathways.

Such deviations may include stretched exponential decay, multi-rate decay, long tails, shoulders, or partial revival. Rather than invalidating the framework, these deviations may encode information about the structure of the underlying environmental Hilbert space. In this sense, the Noise Black Hole framework predicts both the generic exponential form and a route for interpreting deviations from that form.

3.3 Gravitational Black Hole Analogy

The proposed Noise Black Hole should not be confused with a gravitational black hole. The analogy concerns information accessibility rather than gravity.

In a gravitational black hole, matter and information become increasingly inaccessible to external observers. In a Noise Black Hole, coherence and entanglement become increasingly inaccessible as they diffuse into deeper environmental sectors.

The analogy is useful because in both cases information need not be destroyed. Instead, information becomes difficult to access because it is distributed within a larger structure that is not directly observable to the restricted observer. The analogy is intended solely as an intuition for information flow. No claim of physical equivalence is implied.

4 Summary and Conclusions

Scientific theories gain significance not merely by introducing new concepts but by explaining empirical observations. A historical example is Einstein's explanation of Mercury's anomalous perihelion advance, which transformed General Relativity from a mathematical theory into an explanatory framework for observed phenomena. The significance of the present work is similar in spirit. Exponential decoherence is already well established experimentally. The contribution of the Noise Black Hole framework is to show how the generic exponential shape of decoherence may emerge naturally from coherence diffusion and information-theoretic redistribution.

The Structured Quantum Noise framework introduced a view of noise as a structured quantum subsystem rather than a scalar attenuation parameter. The present work identifies a direct explanatory consequence of that view. If coherence can migrate into environmental degrees of freedom, then repeated coherence redistribution naturally generates exponential decoherence.

The distinction is between phenomenology and explanation. Conventional open-system models describe how reduced-system coherence decays; the Noise Black Hole interpretation proposes why the exponential form can emerge from repeated information-theoretic redistribution.

The importance of this result is not that exponential decay can be reproduced. Rather, the significance is that exponential decay emerges as a prediction of an underlying information-theoretic mechanism. In the present context, the empirical law is exponential decoherence. The proposed explanation is coherence diffusion into a Noise Black Hole.

The framework also suggests a broader experimental interpretation. Ideal exponential decay corresponds to approximately uniform retention across redistribution stages. Deviations from ideal exponential behavior may indicate structured memory, environmental modality, partial backflow, or coherent recurrence. Thus the shape of the decoherence curve may contain information about the structure of the noise environment.

We introduced the concept of coherence diffusion into a Noise Black Hole as an information-theoretic interpretation of quantum decoherence. Building upon the Structured Quantum Noise framework, we argued that coherence migrates through a hierarchy of environmental subsystems while remaining globally conserved. A minimal retention model was shown to generate the familiar exponential decoherence law. The result suggests that exponential decoherence may be understood not as a fundamental assumption, but as an emergent prediction of structured coherence redistribution.

Together with the companion papers, this work forms a three-part progression within the Structured Quantum Noise research program. The first paper develops the mathematical formulation of Structured Quantum Noise. The present paper provides an information-theoretic interpretation of decoherence as coherence diffusion into increasingly inaccessible environmental sectors. The vacuum-fluctuations paper then proposes one possible microscopic physical realization of the structured environments assumed by the framework.

The framework establishes a conceptual connection between coherence revival, information conservation, environmental structure, and classical decoherence behavior. It also suggests that deviations from exponential decay may provide signatures of the internal structure, memory, and modality of the environmental Hilbert space. Observed decoherence curves may therefore serve as indirect probes of the structure, memory, and information dynamics of otherwise inaccessible environmental Hilbert spaces. Beyond explaining the generic exponential form of decoherence, the proposed framework suggests that experimentally measured decoherence profiles may become a practical tool for characterizing the architecture, memory, and information dynamics of complex quantum environments.

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