Testing the Reconstructibility of Quantum Coherence in Mesoscopic Systems: An Experimental Framework Based on State Reconstruction

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Abstract

We propose an experimental framework to test the reconstructibility of quantum coherence in mesoscopic systems under controlled variations of an effective gravitational configuration. Without modifying quantum dynamics, the approach probes whether all observed decoherence can be fully accounted for by standard environmental mechanisms.

The protocol relies on statistical state reconstruction. For quasi-Gaussian states, the relevant information is captured by the covariance matrix. An operational observable is defined as the deviation between the measured covariance matrix after evolution and the one predicted from the reconstructed initial state under standard quantum dynamics, including calibrated environmental decoherence.

Under the null hypothesis of full reconstructibility, this deviation remains compatible with zero under a monotonic scan of the control parameter. A reproducible residual contribution would instead signal a breakdown of reconstructibility.

This provides a direct test of whether standard decoherence models give a complete account of observed dynamics.

1 Introduction

Understanding the limits of quantum coherence and its experimental reconstructibility is a central issue at the interface between quantum mechanics and gravity. While closed-system dynamics is unitary, realistic systems interact with their environment, leading to decoherence and an effective loss of accessible phase information [1–3].

In principle, global unitarity implies that coherence can be fully recovered given access to all degrees of freedom. In practice, this information becomes effectively inaccessible, raising the question of whether reconstructibility remains complete under physically realizable conditions.

Several approaches have explored gravity-related limitations of quantum coherence, including collapse models and gravity-induced decoherence mechanisms [4–8], typically relying on modified dynamics.

An alternative perspective is to focus not on the dynamics of decoherence, but on the operational question of reconstructibility: whether all observed decoherence effects can be fully accounted for by known environmental mechanisms under controlled conditions.

We introduce a monotonic control parameter λ representing an effective gravitational configuration, and define reconstructibility as the ability to recover a reference coherence level under admissible local operations.

Here, gravity is not introduced as a source of decoherence, but as a controllable parameter providing a physically meaningful scan variable for exploring possible regime-dependent limitations of reconstructibility.

Recent advances in levitated optomechanics provide a suitable platform for such tests, offering high isolation from environmental noise and precise control of center-of-mass dynamics [9–13].

In this work, we propose an operational framework based on statistical state reconstruction, comparing the experimentally reconstructed state after evolution with the state predicted from the reconstructed initial condition under standard quantum dynamics, including calibrated environmental decoherence.

The central question is whether all observed deviations from quantum coherence can be fully explained by environmental decoherence, or whether a residual limitation of reconstructibility may persist under controlled conditions.

2 Operational definition of reconstructibility breakdown

Definition (Reconstructibility). A quantum state is said to be reconstructible if there exists a sequence of admissible local operations accessible within the experimental setup allowing recovery of interference visibility arbitrarily close to that of a calibrated reference regime.

We define a testable operational criterion for assessing reconstructibility under controlled experimental conditions.

Consider a system prepared in an initial quantum state that can be experimentally reconstructed and subsequently evolved under controlled conditions. The final state is reconstructed from measurement data and independently predicted from the reconstructed initial state using standard quantum dynamics, including calibrated environmental decoherence. The central question is whether these two descriptions remain consistent within experimental uncertainty under systematic variations of an external control parameter λ associated with an effective gravitational configuration.

Operational hypothesis. We test whether reconstructibility exhibits a regime-dependent limitation, defined operationally through the deviation observable Δ, beyond calibrated environmental decoherence.

Deviation observable. We introduce an operational deviation observable quantifying the difference between the reconstructed final state and the state predicted from the reconstructed initial condition under standard quantum dynamics, including calibrated environmental decoherence:

$$\Delta = \|\Sigma_{\text{meas}} - \Sigma_{\text{pred}}\| .$$

Here Σ_{meas} and Σ_{pred} denote the covariance matrices associated with the reconstructed and predicted states, and $\|\cdot\|$ is a suitable matrix norm (e.g. Frobenius norm). The role of Δ is to quantify the mismatch between reconstructed and predicted descriptions; its interpretation depends on the null hypothesis and on its behavior under variations of λ.

Null hypothesis. Under full reconstructibility, Δ is expected to remain statistically compatible with zero across the entire range of λ, once all environmental contributions are calibrated. Any observed deviation can then be attributed to known decoherence mechanisms and experimental uncertainties.

Conversely, a systematic and reproducible deviation, robust under experimental recalibration and refinement of accessible operations, signals a breakdown of reconstructibility at the operational level. Such a deviation is not interpreted as a modification of the underlying unitary dynamics, but as a limitation in the accessible information required for complete state reconstruction.

This formulation is intentionally minimal and purely operational, enabling direct confrontation with experimental data without introducing additional dynamical assumptions.

The key distinction with standard decoherence calibration protocols lies in the systematic search for a residual contribution that remains stable under refinement of environmental modeling and correlates with a controlled parameter, rather than decreasing under improved isolation.

3 Operational meaning and observable

The operational framework can be expressed in terms of statistical state reconstruction and comparison with standard quantum predictions.

We consider a system whose center-of-mass motion is prepared in a near-Gaussian quantum state and reconstructed experimentally through repeated measurements. The state is described in phase space by

$$\mathbf{X} = (x, p)^T,$$

and characterized by its first moments $\langle \mathbf{X} \rangle$ and covariance matrix

$$\Sigma_{ij} = \frac{1}{2}\langle X_i X_j + X_j X_i \rangle - \langle X_i \rangle \langle X_j \rangle.$$

Within the Gaussian approximation, Σ fully specifies the state.

After preparation, the system evolves under controlled conditions, including calibrated environmental decoherence and a tunable parameter associated with an effective gravitational configuration. The final state is reconstructed, yielding Σ_{meas}, while the reconstructed initial state is propagated under standard quantum dynamics to obtain Σ_{pred}.

The predicted evolution follows

$$\Sigma_{\mathrm{pred}}(t) = \Phi(t)\, \Sigma_0\, \Phi^T(t) + \Sigma_{\mathrm{env}}(t),$$

where $\Phi(t)$ is the phase-space evolution matrix associated with the effective Hamiltonian, and $\Sigma_{\mathrm{env}}(t)$ accounts for calibrated environmental decoherence.

The deviation observable is

$$\Delta(t) = \left\| \Sigma_{\mathrm{meas}}(t) - \Phi(t)\, \Sigma_0\, \Phi^T(t) - \Sigma_{\mathrm{env}}(t) \right\|,$$

or equivalently

$$\Delta = \|\Sigma_{\mathrm{meas}} - \Sigma_{\mathrm{pred}}\|.$$

A natural choice is the Frobenius norm, $\Delta = \sqrt{\mathrm{Tr}[(\Sigma_{\mathrm{meas}} - \Sigma_{\mathrm{pred}})^2]}$.

Under the null hypothesis of full reconstructibility, one expects

$$\Delta \approx 0$$

within experimental uncertainties after calibration of all relevant decoherence channels. In particular, a monotonic scan of the control parameter should not introduce any systematic residual.

Conversely, a reproducible and parameter-dependent deviation, robust under experimental recalibration, signals a breakdown of reconstructibility.

This formulation directly connects reconstructibility to experimentally accessible quantities.

4 Experimental platforms

The deviation observable defined above can be implemented across several experimental platforms. We briefly compare these and motivate the choice of levitated optomechanics.

Comparison of experimental platforms

Matter-wave interferometry directly probes spatial coherence through interference visibility, but typically relies on ensemble measurements and is subject to complex environmental decoherence, making precise reconstruction-based tests challenging.

Gravity-mediated entanglement proposals (e.g. Bose–Marletto–Vedral (BMV)-type experiments [14, 15]) probe the quantum nature of gravity through inter-system correlations, but do not directly address the reconstructibility of single-system quantum states and involve additional experimental complexity.

Levitated optomechanics as a candidate platform

Levitated optomechanical systems provide a favorable platform for implementing the proposed protocol. Neutral nanoparticles can be trapped, cooled close to their motional ground state, and released into controlled free evolution [10, 11], enabling both precise control of center-of-mass motion and statistical state reconstruction.

A key advantage is the ability to minimize and calibrate environmental decoherence channels, ensuring that any observed deviation cannot be attributed to incomplete modeling of known mechanisms. In addition, the free-evolution phase allows controlled variation of external parameters, including gravitational configurations, without introducing uncontrolled couplings.

These features make levitated nanoparticles particularly well suited for monotonic parameter scans and for testing the robustness of reconstructed states under controlled perturbations. Recent advances in ground-state cooling, long coherence times, and precision measurements indicate that deviations at the level of second moments may already be experimentally accessible.

Implementation of the control parameter

The gravitational parameter scan can be implemented through controlled variations of the effective gravitational potential during free evolution, for instance by modifying the vertical position of the setup or by introducing a tunable nearby mass distribution.

The relevant quantity is an effective gravitational configuration entering the system Hamiltonian. A parameter λ can be introduced to characterize this controlled variation, for example through $V_g(x) = mgx$ or through an externally generated gradient. This enables systematic exploration of reconstructibility under monotonic parameter variation while keeping all other conditions fixed.

The sensitivity required to resolve a residual contribution Δ_{res} depends on its magnitude, which is not specified within the present framework.

Phenomenological anchoring. In the absence of a predefined scale, possible deviations may be parametrized phenomenologically, either as a continuous residual contribution or as a threshold-like behavior in terms of an effective parameter combining mass, spatial delocalization, interrogation time, and gravitational configuration.

This parametrization introduces no additional dynamics but allows null results to be translated into quantitative constraints within standard sensitivity analyses.

5 Expected signatures

The goal is not to detect a new decoherence mechanism, but to identify deviations from the expectation that all decoherence effects can be fully accounted for by calibrated environmental contributions.

Within the operational framework, the relevant observable is

$$\Delta = \|\Sigma_{\text{meas}} - \Sigma_{\text{pred}}\|.$$

A central aspect of the protocol is the controlled variation of an external parameter λ, parametrizing a modification of the effective gravitational configuration. The observable Δ is therefore analyzed as a function of λ.

Under standard quantum dynamics, once all decoherence channels are calibrated, one expects

$$\Delta(\lambda) \approx 0$$

within experimental uncertainties. Any residual discrepancy should decrease under improved calibration.

A deviation may be decomposed as

$$\Delta = \Delta_{\text{env}} + \Delta_{\text{res}},$$

where Δ_{env} accounts for known decoherence mechanisms and Δ_{res} denotes any residual contribution beyond calibrated effects.

A key feature of a non-trivial residual contribution is its robustness under experimental recalibration: environmental noise should vary under changing conditions, whereas a genuine residual contribution remains stable.

Under the null hypothesis,

$$\frac{d\Delta}{d\lambda} \approx 0$$

within statistical fluctuations. In contrast, a reproducible dependence

$$\frac{d\Delta}{d\lambda} \neq 0$$

constitutes a distinctive signature.

The expected effect need not correspond to a sharp threshold, but may instead appear as a gradual departure over a specific region of parameter space.

The key distinction is that Δ_{res} represents a limitation that cannot be removed by refinement of experimentally accessible operations, and is therefore operationally distinguishable from standard decoherence.

6 Falsification condition

Operational criterion. The hypothesis is falsified if reconstructibility remains achievable under all admissible operations for increasing values of λ, with no persistent deviation beyond calibrated environmental contributions.

Within the operational definition adopted here, the deviation Δ can be decomposed as

$$\Delta = \Delta_{\text{env}} + \Delta_{\text{res}},$$

where Δ_{env} accounts for known decoherence mechanisms and Δ_{res} represents any contribution that cannot be eliminated through improved environmental modeling or refinement of admissible operations.

The null result corresponds to

$$\Delta_{\text{res}} = 0$$

within experimental uncertainties across the explored parameter range, equivalently

$$\Delta(\lambda) \approx 0$$

after calibration of all known decoherence channels.

Conversely, a positive signal requires

$$\Delta_{\text{res}} \neq 0, \quad \frac{d\Delta}{d\lambda} \neq 0,$$

which cannot be absorbed into improved modeling of known environmental decoherence mechanisms.

This falsification condition applies to the operational scenario considered here and is therefore restricted to the class of experimental configurations under investigation.

This criterion directly tests the completeness of standard decoherence models within the explored regime.

7 Conclusion

We have proposed an operational framework to test the reconstructibility of quantum coherence in mesoscopic systems through statistical state reconstruction.

The approach does not modify quantum dynamics, but tests whether standard decoherence models fully account for observed effects. The proposed observable provides a direct experimental probe of this question.

Levitated optomechanics offers a promising platform for implementation, with current capabilities potentially sufficient to detect deviations depending on their magnitude.

This framework provides a direct experimental test of whether standard decoherence models give a complete account of observed dynamics.

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