Apparatus-Dependent Decoherence in Matter-Wave Interferometry from an Interface-Constrained Dynamics Ansatz

AuraCoreCF Research Group

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Abstract

We formulate a testable phenomenology in which finite-resolution measurement interfaces (gratings, masks, detectors, readout optics) induce an additional position-localizing decoherence channel whose strength depends explicitly on the interface resolution d. Using an explicit Gaussian unsharp-position instrument, we derive a Lindblad generator of the form $\dot{\rho} = -\frac{i}{\hbar}[H,\rho] - k(d)\,[\hat{x},[\hat{x},\rho]]$. Dimensional consistency and minimal matching to an action-level Fisher-information stiffness fix the scaling $k(d) \propto \hbar/(m^* d^4)$ (up to a dimensionless kernel factor η). We then derive visibility suppression laws for Talbot–Lau / KDTLI geometries, including the correct dependence of the relevant path separation Δx on grating period d. This yields sharp discrimination protocols expressed in terms of independent laboratory knobs (d, L, v): at fixed Talbot order one predicts $\ln(V/V_{\mathrm{QM}}) \propto -1/d^2$, while at fixed Δx one predicts $\ln(V/V_{\mathrm{QM}}) \propto -1/d^4$. Finally, we translate reported high-mass interferometry performance into a conservative bound on the mass scale m^* in terms of an allowed "unexplained visibility loss" budget, emphasizing how to avoid double-counting losses already included in experimental visibility models.

1 Scope and claim level

This paper is deliberately *phenomenological*. We do *not* claim a microscopic derivation of detector dynamics. The goal is to: (i) specify an explicit interface model, (ii) obtain a completely positive Markovian master equation, (iii) identify a laboratory discriminator that cannot be absorbed into standard environment-only models without introducing a new d-dependent mechanism.

2 Gaussian finite-resolution interface as a quantum instrument

Let ρ be the system density operator and $\hat{x}$ the transverse position operator relevant for readout. A Gaussian unsharp-position measurement of resolution d is represented by Kraus operators

$$M(y) = (2\pi d^2)^{-1/4} \exp\left[-\frac{(\hat{x}-y)^2}{4d^2}\right], \qquad y \in \mathbb{R}. \tag{1}$$

The non-selective (unconditional) map is

$$\Phi_d(\rho) = \int_{\mathbb{R}} dy\, M(y)\rho M^\dagger(y). \tag{2}$$

In the position basis,

$$\langle x|\Phi_d(\rho)|x'\rangle = \rho(x,x') \exp\left[-\frac{(x-x')^2}{8d^2}\right]. \tag{3}$$

If such "hits" occur at Poisson rate r (hits per unit time), then for small Δt

$$\rho \mapsto (1 - r\Delta t)\rho + r\Delta t\, \Phi_d(\rho),$$

and expanding (3) to leading order yields the Lindblad generator

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - \frac{r}{8d^2}\,[\hat{x}, [\hat{x}, \rho]] + O(d^{-4} \text{ corrections}), \tag{4}$$

with $k = \frac{r}{8d^2}$. This is standard continuous-measurement physics and guarantees complete positivity.

Referee pre-emption. The double-commutator structure is *not* novel; what is novel is the proposed d-dependence of r when the interface is treated as a physical subsystem with a coherence-constraining stiffness.

3 Units-closed matching and the forced d^{-4} scaling

The coefficient k in (4) must have units

$$[k] = \frac{1}{(\text{length})^2 \cdot (\text{time})},$$

since $[\hat{x}, [\hat{x}, \rho]]$ carries $(\text{length})^2$.

Assume the interface-induced channel is controlled by: (i) $\hbar$, (ii) a single mass scale m^* setting an information-gradient stiffness, and (iii) the interface resolution length d. Then the only way to build k from $(\hbar, m^*, d)$ is

$$k(d) = \frac{\eta\,\hbar}{8\,m^*\,d^4}, \tag{5}$$

where η is dimensionless and captures kernel conventions and dimensional reductions. Indeed $\hbar/(m^* d^4)$ has units $1/(\text{length})^2\text{time}$, while $\hbar/(m^* d^2)$ does not.

Equivalently, comparing (4) and (5) implies

$$r(d) = \eta\,\frac{\hbar}{m^* d^2}. \tag{6}$$

Minimal matching rationale (explicitly non-microscopic). If an action-level Fisher stiffness penalizes density gradients on scale d by an energy $E_C(d) \sim \hbar^2/(8m^* d^2)$, then the minimal associated dynamical rate is $r \sim E_C/\hbar \sim \hbar/(8m^* d^2)$, consistent with (6) (with η absorbing geometric factors).

4 Visibility suppression for a given path separation

In the position basis, the decoherence term yields

$$\rho(x, x'; t) = \rho(x, x'; 0)\exp\left[-k(d)\,t\,(x - x')^2\right]. \tag{7}$$

For an interferometer in which the relevant coherence is between two paths separated by Δx over coherence time t,

$$\frac{V}{V_{\text{QM}}} = \exp\left[-k(d)\,t\,(\Delta x)^2\right] = \exp\left[-\frac{\eta\hbar}{8m^*}\,\frac{t(\Delta x)^2}{d^4}\right]. \tag{8}$$

5 Talbot–Lau / KDTLI geometry: how Δx depends on d

For a grating of period d illuminated by a matter wave of de Broglie wavelength $\lambda_{\rm dB} = h/(mv)$, diffraction order n has small angle $\theta_n \simeq n\lambda_{\rm dB}/d$, giving transverse displacement after propagation L

$$x_n \simeq L\theta_n \simeq n\frac{\lambda_{\rm dB}L}{d}. \tag{9}$$

Thus the separation between adjacent orders is

$$\Delta x \sim \frac{\lambda_{\rm dB}L}{d}. \tag{10}$$

Near Talbot resonance, the relevant grating separation satisfies

$$L \simeq q\,L_T, \qquad L_T = \frac{d^2}{\lambda_{\rm dB}}, \tag{11}$$

with Talbot order $q \in \{1, 1/2, 2, \dots\}$. Substituting into (10),

$$\Delta x \sim \frac{\lambda_{\rm dB}(qd^2/\lambda_{\rm dB})}{d} = q\,d. \tag{12}$$

6 Two discriminator protocols in terms of independent knobs (d, L, v)

Equation (8) plus the geometry relations yield two clean scaling tests.

Protocol A: fixed Talbot order q (Talbot-resonant scan)

Hold Talbot order q fixed while varying d, and adjust v (hence $\lambda_{\rm dB}$) to maintain $L = qd^2/\lambda_{\rm dB}$. Using (12) in (8) gives

$$\ln\!\left(\frac{V}{V_{\rm QM}}\right) = -\frac{\eta\hbar}{8m^*}\frac{t\,q^2}{d^2}. \tag{13}$$

Prediction: $\ln(V/V_{\rm QM})$ is linear in $1/d^2$ at fixed q.

Protocol B: fixed path separation Δx (geometry-controlled scan)

Hold Δx fixed while varying d by adjusting L and/or v to satisfy $\Delta x = \lambda_{\rm dB}L/d$. Then (8) yields

$$\ln\!\left(\frac{V}{V_{\rm QM}}\right) = -\frac{\eta\hbar}{8m^*}\frac{t\,(\Delta x)^2}{d^4}. \tag{14}$$

Prediction: $\ln(V/V_{\rm QM})$ is linear in $1/d^4$ at fixed Δx.

Referee pre-emption ("changing d changes everything"). These protocols explicitly specify what is held fixed and which knobs must be co-tuned. They are designed to separate genuine d-dependence from indirect changes in Δx, velocity spread, diffraction efficiency, surface phases, etc.

7 Conservative bounds from existing experiments

Let an experiment report an "expected" visibility model $V_{\rm model}$ that accounts for known loss channels (velocity spread, finite coherence, known scattering, etc.), and observe $V_{\rm obs}$. Define an *unexplained loss budget* $\varepsilon \in (0,1)$ by

$$\frac{V_{\rm obs}}{V_{\rm model}} \geq 1-\varepsilon. \tag{15}$$

Interpreting the interface-induced channel as contributing at most this residual loss gives

$$\ln\left(\frac{V_{\rm obs}}{V_{\rm model}}\right) \geq \ln(1-\varepsilon) \simeq -\varepsilon \qquad (\varepsilon \ll 1). \tag{16}$$

Using (13) (Talbot-resonant operation, $\Delta x \simeq qd$) yields the bound

$$m^* \gtrsim \frac{\eta\hbar\, t\, q^2}{8d^2\,|\ln(1-\varepsilon)|}. \tag{17}$$

This form is deliberately conservative and avoids double-counting loss mechanisms already included in $V_{\rm model}$.

8 Discussion: what would falsify the proposal

A null result in either Protocol A or B—i.e. no correlation of $\ln(V/V_{\rm QM})$ with $1/d^2$ (Protocol A) or $1/d^4$ (Protocol B) beyond known systematics—would constrain m^* upward via (17). Conversely, a reproducible scaling law matching (13) or (14) across different grating technologies (material, optical, phase gratings) would indicate a decoherence mechanism not captured by standard environment-only models.

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References

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A Appendix A: Conventional d-Dependent Systematics and How to Separate Them

A central referee concern is that changing the grating period d changes many aspects of near-field interferometers, potentially producing spurious correlations between visibility and d. Here we (i) list dominant conventional mechanisms with possible d-dependence, (ii) state which ones are removed by the proposed protocols, and (iii) specify cross-checks that prevent misattribution of ordinary effects to the interface-induced channel.

A.1 A.1 Overview: what is claimed vs. what is not

The proposal in the main text is not that visibility is *independent* of d in standard physics. In real devices, V often varies with d for mundane reasons. The claim is:

> There exists an additional Markovian localization channel whose contribution to $\ln(V/V_{\rm QM})$ scales as $-1/d^2$ at fixed Talbot order (Protocol A) and as $-1/d^4$ at fixed path separation (Protocol B), and this scaling should persist across grating technologies when environmental parameters are controlled.

The appendices below spell out what must be controlled or independently measured to make that inference.

A.2 A.2 Grating–particle interactions: van der Waals / Casimir–Polder phases

For material gratings, near-surface potentials modify the phase accumulated in each slit and can reduce contrast by dephasing across the transverse momentum distribution. The strength depends on slit width, thickness, and surface properties; it can correlate with d if the grating fabrication keeps fixed duty cycle (slit fraction) or thickness-to-period ratio.

Mitigation. Use (i) optical phase gratings (Kapitza–Dirac) where surface forces are absent, or (ii) compare multiple grating technologies at the same d. An effect that persists with comparable scaling under both material and optical gratings is difficult to attribute to surface potentials. Additionally, independently characterize the phase profile via known Casimir–Polder models and include it in $V_{\rm model}$; the bound in the main text is defined using the *residual* ratio $V_{\rm obs}/V_{\rm model}$ to avoid double counting.

A.3 A.3 Diffraction efficiency, open fraction, and higher-order contributions

Changing d at fixed fabrication constraints can change open fraction, grating bar width, and diffraction efficiencies. This modifies the relative weights of interfering paths, which changes V even without decoherence.

Mitigation. Protocol A fixes Talbot order and requires co-tuning v (hence $\lambda_{\rm dB}$) to maintain resonance. In addition, one should measure the transmitted intensity pattern and extract the effective Fourier coefficients of the grating transmission function. These coefficients enter the *coherent* interference prediction $V_{\rm QM}$ and can be accounted for in $V_{\rm model}$. The interface-induced channel is inferred only from residual losses beyond this model.

A.4 A.4 Velocity spread and longitudinal coherence

Visibility in Talbot–Lau devices is sensitive to the velocity distribution: different velocities correspond to different Talbot lengths, producing phase averaging. If changing d requires changing v to maintain Talbot order, one must ensure the *relative* velocity spread $\Delta v/v$ is controlled, else V may vary due to averaging.

Mitigation. Use velocity selection such that $\Delta v/v$ is held fixed (or measured) across the scan, and propagate the measured distribution through the standard Talbot transfer theory to define V_{model}. This is a standard control in high-precision KDTLI analyses.

A.5 A.5 Mechanical vibrations and grating misalignment

Phase noise from vibrations and misalignment can reduce visibility. If different gratings with different d have different mechanical stiffness or mounting, an apparent d-trend can occur.

Mitigation. Use the same mechanical mounts where possible, measure vibration spectra, and include a phase-noise model (or perform active stabilization). A particularly strong control is to repeat the d-scan using *optical gratings* (no moving nanostructures) or to rotate between gratings without changing mounts.

A.6 A.6 Collisional and thermal decoherence (environmental)

Gas collisions and thermal emission depend on pressure, temperature, particle size, and flight time. They do not depend directly on d except indirectly through changes in trajectory or time-of-flight.

Mitigation. Perform pressure scans at fixed d to fit environmental decoherence parameters, and then hold pressure fixed while varying d. If a d-dependence remains at constant environment and fixed t and Δx (Protocol B), it is not explained by standard environmental models without introducing an additional d-dependent mechanism.

A.7 A.7 Why the proposed scalings are hard to fake across technologies

Most mundane d-dependencies are strongly *technology specific*: surface phases for material gratings, diffraction efficiencies tied to fabrication, or mechanical noise tied to mounts. By contrast, the proposed interface-induced term depends only on the operational resolution scale d and (in the minimal model) not on microscopic details.

Cross-technology falsification strategy. Perform Protocol A or B using at least two distinct grating realizations:

1. material absorptive gratings,
2. optical phase gratings (Kapitza–Dirac),
3. ionizing standing-wave gratings (OTIMA-style).

A common scaling $\ln(V/V_{\text{QM}}) \propto -1/d^2$ (Protocol A) or $-1/d^4$ (Protocol B) appearing with comparable slope in all technologies would be difficult to attribute to technology-specific systematics.

A.8 A.8 Practical "referee-proof" reporting checklist

To make a d-scan publishable, report:

- measured (d, L, v) and $\Delta v/v$ for each run,
- measured pressure and temperature,
- a coherent-transfer model for V_{QM} including grating Fourier coefficients,
- an environmental decoherence model fitted from pressure scans,
- the residual ratio $V_{\mathrm{obs}}/V_{\mathrm{model}}$ vs. d with uncertainty,
- cross-technology repetition or a clear argument why systematics cannot mimic the scaling.