Interface-Constrained Dynamics and Apparatus-Dependent Decoherence (Units-Consistent Matching, Gaussian Kernel, Talbot–Lau Geometry, and Updated Bounds)

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Abstract. We revise and consolidate the interface-induced decoherence proposal by (i) fixing the action→master-equation matching so all units close, (ii) specifying an explicit Gaussian coarse-graining (unsharp-position) instrument and computing the dimensionless kernel factor η, (iii) deriving the relevant path-separation scale Δx(d) for a Talbot–Lau/Kapitza–Dirac–Talbot–Lau interferometer, and (iv) recomputing experimental bounds using reported parameters from high-mass KDTLI (LUMI) data. The corrected matching necessarily introduces an additional d-dependence: the Lindblad coefficient scales as ■/(m* d^4), so that for Talbot-resonant operation (Δx≈d) the visibility suppression scales as exp[−const·(■ t)/(m* d^2)]. We give an experimentally implementable discriminator in terms of independent knobs (d, grating separation L, and beam velocity v) and provide updated order-of-magnitude bounds on m* under a clearly stated convention.

1. Context and what is being fixed. Prior drafts introduced (a) a Fisher-information (information-gradient) term in the action and (b) an interface-induced position-localizing Lindblad generator. The qualitative picture is retained, but the original mapping k∝■/(m* d^2) was dimensionally inconsistent: the monitoring strength k multiplying [x,[x,ρ]] must have units ($\text{length}^{-2}\ \text{time}^{-1}$). This revision derives a units-consistent coefficient and makes the "apparatus dependence" claim precise for near-field interferometers.

2. Action-level coherence constraint (recap). We start from the interface-constrained action term

$$S_C = -\,(■^2 / (8\, m^*)) \int d■x \,\sqrt{(-g)}\, g^{\mu\nu}\, (\nabla_\mu n\, \nabla_\nu n)/n$$

where n≡√|j·j| for a conserved matter current j^μ. In the nonrelativistic single-particle limit $\psi=\sqrt{\rho}\, e^{iS/■}$, this reduces to the Fisher-information functional

$$S_C \to -\,(■^2 / (8\, m^*)) \int dt\, d^3x\, (\nabla\rho)^2 / \rho.$$

We interpret this as an information-gradient stiffness penalizing sharp density variations, controlled by a single mass scale m*.

3. Explicit Gaussian interface and η from first principles. We model a finite-resolution spatial interface as an *unsharp position instrument* (a Gaussian POVM/instrument). Let d be the interface resolution (standard deviation). The Kraus operators are

$$M(y) = (2\pi\, d^2)^{-1/4} \exp(\, -\, (x■ - y)^2 / (4\, d^2)\,),$$

with outcome y∈■ and ∫dy M(y)†M(y)=I. A single (non-selective) unsharp measurement acts as $\Phi_d(\rho)$=∫dy M(y)ρM(y)†. In the x-basis this gives the well-known Gaussian dephasing:

$$\rho(x,x')\ ■\ \rho(x,x') \exp(\, -\, (x-x')^2 / (8\, d^2)\,).$$

If the interface performs such weak measurements at Poisson rate r (hits per second), then for small dt we have ρ(t+dt)= (1−r dt)ρ + r dt $\Phi_d(\rho)$, which yields the Markovian master equation

$$d\rho/dt = -(r/(8\, d^2))\, [x■,[x■,\rho]] + O(d■■ \text{ corrections to higher moments}).$$

Thus, for a Gaussian coarse-graining kernel the numerical factor in the localization generator is fixed: the double-commutator coefficient is $k = r/(8\, d^2)$. This fixes the “kernel factor” η once r is specified.

4. Units-consistent matching: from Fisher stiffness to monitoring rate. The Fisher term sets an energy scale against density gradients on length d. For a normalized 1D Gaussian packet $\rho(x)\propto\exp(-x^2/(2d^2))$, one has the Fisher information $I\equiv\int dx\, (\partial\rho)^2/\rho = 1/d^2$. Plugging into the nonrelativistic density form suggests an interface-induced energy scale per “coarse-grained degree of freedom”

$$E_C(d) \sim (\blacksquare^2/(8\, m^*))\, (1/d^2).$$

The minimal associated dynamical rate is $r \sim E_C/\blacksquare = \blacksquare/(8\, m^*\, d^2)$. We parameterize possible order-unity ambiguities (exact dimensional reduction, multi-D factors, kernel conventions) with a dimensionless constant η and write

$$r = \eta \cdot \blacksquare/(m^*\, d^2).$$

Combining with $k=r/(8\, d^2)$ yields the **units-consistent** localization strength

$$k = \eta \cdot \blacksquare\, /\, (8\, m^*\, d\blacksquare).$$

Therefore the corrected master equation is

$$d\rho/dt = -(i/\blacksquare)[H,\rho] - (\eta\, \blacksquare\, /\, (8\, m^*\, d\blacksquare))\, [x\blacksquare,[x\blacksquare,\rho]].$$

All units now close: $[k]=1/(m^2\cdot s)$, because $\blacksquare/(m^*\, d\blacksquare)$ has units $1/(m^2\cdot s)$. For the specific Gaussian-instrument derivation above, taking $r\approx E_C/\blacksquare$ gives $\eta\approx 1/8$ as a natural “no-free-parameters” convention; we keep η explicit for transparency.

5. Visibility law and where d-dependence does (and does not) cancel. In position representation, the corrected master equation gives

$$\rho(x,x';t)=\rho(x,x';0)\, \exp(\, -k\, t\, (x-x')^2\,),$$

so the visibility relative to ideal quantum prediction is

$$V/V_{QM} = \exp(\, -k\, t\, (\Delta x)^2\,) = \exp(\, -\, (\eta\, \blacksquare\, t\, /(8\, m^*\, d\blacksquare))\, (\Delta x)^2\,).$$

Importantly, **d-dependence depends on what is held fixed**: **Fixed Δx (geometry adjusted so the interfering separation is constant):** $\ln(V/V_{QM}) \propto -1/d\blacksquare$. **Talbot-resonant near-field operation, where Δx scales with d:** $\ln(V/V_{QM}) \propto -1/d^2$. The earlier cancellation (setting $\Delta x=d$ inside a model where $k\propto 1/d^2$) is resolved: with the corrected $k\propto 1/d\blacksquare$, Talbot operation still yields a robust $1/d^2$ signature.

6. Talbot–Lau / KDTLI geometry: $\Delta x(d)$ and independent knobs. Consider diffraction at a grating of period d. For small angles, the nth diffraction order has angle $\theta_n \approx n\, \lambda_{dB}/d$, so after propagation length L the transverse displacement is $x_n \approx n\, \lambda_{dB}\, L\, /\, d$. The separation between adjacent orders is therefore

$$\Delta x \approx \lambda_{dB}\, L\, /\, d.$$

In a Talbot–Lau interferometer, strong near-field self-imaging occurs near the Talbot length $L_T=d^2/\lambda_{dB}$. At Talbot resonance ($L\approx q\cdot L_T$ for integer/half-integer order q),

$$\Delta x \approx (\lambda_{dB}\, L)/d \approx (\lambda_{dB}\, (q\, d^2/\lambda_{dB}))/d = q\, d.$$

Thus Δx scales linearly with d for fixed Talbot order q.

Independent knobs (what can actually be held fixed in the lab). In practice, the experimenter can vary: **d**: choice of grating period (material gratings) or laser wavelength (optical phase grating). **L**: grating separation (rebuild/translate stages) and total baseline. **v**: mean velocity selected by time-of-flight gating; λ_{dB}=h/(mv). This enables two clean discrimination protocols: **Protocol A (Talbot-resonant scan):** keep Talbot order q fixed by adjusting v so that L≈q d²/λ_{dB}. Then Δx≈q d and the theory predicts ln(V/V_{QM}) ∝ –t/(m* d²) at fixed q. **Protocol B (fixed Δx scan):** choose a target separation Δx_0 and, for each d, set L = (Δx_0 d)/λ_{dB} (adjusting L and/or v). Then ln(V/V_{QM}) ∝ –t/(m* d■) at fixed Δx_0. Either protocol is distinct from standard environmental decoherence, where the dominant gas-collision or thermal emission rates do not depend on the grating period once Δx, pressure, temperature, and transit time are held fixed.

7. Updated bounds from high-mass KDTLI (LUMI) parameters. Fein et al. (Nature Physics 2019) report a 2 m-long Talbot–Lau interferometer (LUMI) with grating period d=266 nm and grating separation L≈0.98 m (total baseline ≈1.96 m), and a Gaussian velocity distribution with mean v■=261 m/s. They state that the interference fringes reach more than 90% of the expected quantum visibility. Under Talbot-like operation (Δx≈d), our corrected visibility law gives

$$V/V_{QM} = \exp(- \eta ■ t /(8 m^* d^2)), \text{ with } t = (1.96\text{ m})/v■.$$

Using $V/V_{QM} \geq 0.90$, v■=261 m/s, d=266 nm gives t≈7.510e-03 s and therefore the bound

$$m^* \geq (\eta ■ t)/(8 d^2 \ln(1/0.90)) \approx 1.66\text{e-}24 \text{ kg} \times (\eta/(1/8)).$$

With the explicit Gaussian-instrument matching choice η=1/8, this is **m* ■ 1.66e-24 kg** ≈ **1000 amu**. If one instead adopts a more conservative “η≈1” order-unity convention, the bound is 8× larger: m* ■ 1.33e-23 kg ≈ 7997 amu.

These numbers are *not* fine-tuned: they follow directly from the corrected dimensional matching plus the reported experimental parameters.

8. What survives a skeptical check (and what does not). Survives: A position-localizing Lindblad channel is a standard, well-posed CPTP modification; specifying an instrument (Gaussian) and deriving the double-commutator structure is straightforward. **Survives:** Once the coefficient is required to come from ■ and a single mass scale m*, dimensional analysis forces an additional d-dependence. Any phenomenology that claims “apparatus dependence” should be written in terms of the independent knobs (d,L,v) as in Protocol A/B. **Open:** The step from an action-level Fisher term to an effective monitoring rate r is still an *effective* argument; η encodes the details of coarse-graining in spacetime and how many degrees of freedom are being “rendered”. The paper now makes this explicit instead of hiding it in inconsistent units.

9. Conclusion. A coherent interface-constrained story can be told in which a Fisher-information stiffness in the matter action induces an apparatus-dependent localization channel in the reduced dynamics. The key correction is that the Lindblad coefficient must scale as ■/(m* d■). For Talbot-resonant near-field interferometers (Δx≈d), this yields a clean 1/d² visibility signature. Using reported LUMI parameters, one obtains m* bounds in the ~10^3–10■ amu range (depending on η convention), which is already highly testable by re-analysing multi-grating-period datasets or by running Protocol A/B scans.

References.

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