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Article

Quantum effects in weak gravitational fields: towards tabletop tests of quantum gravity

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Abstract. This study explores quantum effects in weak gravitational fields with the aim of identifying feasible pathways towards tabletop tests of quantum gravity. Using numerical simulations of matter-wave interference for nanoparticles with masses between 10^{-17} and 10^{-15} kg, we investigate how environmental and fundamental decoherence mechanisms shape observable signatures. The results reveal a mass-dependent reduction in interference visibility, dropping from near unity at 10^{-17} kg to below 0.2 at 10^{-15} kg. Coherence times were found to exceed one second for particles lighter than 10^(-16) kg under cryogenic ultra-high-vacuum conditions, but decreased to sub-millisecond scales for 10^{-15} kg particles at room temperature, confirming thermal radiation as the dominant source of decoherence. In parallel, collapse models such as CSL predict additional suppression of visibility for interrogation times of 0.1 s, particularly for masses above 10^{-16} kg, enabling discrimination between environmental and intrinsic decoherence mechanisms. These findings underscore the necessity of maintaining ultra-high vacuum and cryogenic environments to detect gravitationally induced quantum phases, thereby providing a practical framework for near-future interferometry experiments. While the present work is limited to phenomenological models and simulated data, it establishes a roadmap for extending investigations to heavier mass regimes, incorporating realistic noise sources, and testing alternative collapse scenarios.
Keywords: quantum gravity, weak gravitational fields, nanoparticle interferometry, decoherence, coherence times, collapse models, CSL, cryogenic ultra-high vacuum, gravitational phases, tabletop experiments.

1. Introduction

The unification of quantum mechanics and general relativity remains one of the central unsolved problems of modern physics. Quantum mechanics successfully describes microscopic systems, while general relativity governs the dynamics of spacetime and gravitation at macroscopic scales. Despite their respective successes, the two frameworks are fundamentally incompatible in regimes where both quantum and gravitational effects are relevant. Direct access to the Planck scale is experimentally impossible, which has led to growing interest in indirect tests of quantum gravity under weak-field conditions. Among the most promising approaches are tabletop interferometry experiments with mesoscopic particles, which offer the potential to reveal gravitationally induced quantum phases in controlled laboratory environments.

Matter-wave interferometry provides a unique opportunity to test the persistence of quantum superpositions for particles approaching the classical–quantum boundary. However, these systems are highly sensitive to environmental noise, making it difficult to separate signatures of fundamental decoherence from those of thermal radiation, gas collisions, and technical imperfections. The scientists [1] first demonstrated that nanoparticles could, in principle, be prepared in macroscopic superpositions if sufficiently cooled and isolated, establishing a theoretical foundation for laboratory-scale tests. Building on this, the authors [2] proposed free nano-object Ramsey interferometry and showed that while quantum superpositions are feasible, coherence is strongly limited by thermal emission at room temperature. The research team [3] extended these studies by applying the Continuous Spontaneous Localization (CSL) model, predicting additional visibility suppression for particles exceeding 10^{-16} kg. Carney et al. [4] emphasized the importance of identifying experimental regimes where collapse-model signatures could be isolated from environmental effects, providing a roadmap for tabletop quantum gravity experiments. Tebbenjohanns et al. [5] advanced the experimental frontier by achieving near-ground-state control of a levitated nanoparticle in cryogenic free space, demonstrating feasibility of ultra-isolated large-mass interferometry.

More recently, progress has been made toward mitigating environmental decoherence under less extreme conditions. Dania et al. [6] reported quantum optomechanics of a levitated nanoparticle at room temperature with over 90% state purity, achieved by exploiting coherent scattering into a high-finesse optical cavity. This result demonstrates that ground-state-like behavior can be maintained without cryogenics, significantly extending the parameter space for future interferometry. In parallel, Neumeier et al. [7] presented experimental and theoretical analysis of fast quantum interference in 100-nm silica nanoparticles using optical time-bin splitting, highlighting how delocalization and interference visibility evolve under realistic decoherence rates. Together, these studies indicate that both experimental control and theoretical modeling are reaching the precision required to test gravitationally induced phases at mesoscopic scales.

Despite these advances, a fundamental gap persists: no systematic framework yet exists to jointly account for environmental decoherence and collapse-model predictions in realistic interferometry scenarios. Current approaches tend to emphasize either technical noise suppression or idealized collapse dynamics, leaving open the critical question of how to unambiguously attribute loss of coherence to environmental or fundamental causes.

We hypothesize that combining matter-wave interference simulations with both environmental and collapse-model decoherence mechanisms can identify specific regimes—defined by particle mass, interrogation time, and environmental parameters—where gravitationally induced quantum phases are experimentally detectable. In particular, we expect that ultra-high vacuum and cryogenic conditions will remain essential for maintaining coherence above 10^{-16} kg, while collapse models such as CSL will introduce measurable deviations in fringe visibility that cannot be explained by environmental noise alone.

The objective of this study is to systematically analyze interference visibility and coherence times for nanoparticles in the mass range of 10^{-17} – 10^{-15} kg under varying thermal and pressure conditions, incorporating collapse-model dynamics into the simulations. By doing so, we aim to establish practical criteria for designing tabletop experiments capable of probing weak-field quantum gravity. The novelty of this work lies in unifying environmental and collapse-induced decoherence within a single quantitative framework, thereby offering a realistic roadmap for future experimental efforts at the intersection of quantum mechanics and gravitation.

2. Methods

2.1 Materials and system parameters

Simulations were designed for levitated dielectric nanoparticles with masses in the range of 10^{-17}– 10^{-15} kg, corresponding to silica spheres of radius 50–200 nm and density 2200 kg/m^3, consistent with commonly used experimental systems [8], [9]. The interferometric scheme assumed ultra-high vacuum conditions (10^{-12}– 10^{-9} mbar) and environmental temperatures between 0.1 K and 300 K, as representative of dilution refrigerators, cryogenic cryostats, and room-temperature setups.

2.2 Interferometric setup

We modeled a Mach–Zehnder–type interferometer with optical or magnetic beam splitters, variable arm length L = 0.02 – 0.20 m, and path separation Δx = 50 – 600 nm. Trapping frequencies were varied between 50 and 300 kHz. Phase accumulation from gravitational potential was included as an additive phase term ϕ_g = βm, with β calibrated to ensure values below one radian for the studied mass range [10].

2.3 Simulation procedure

The interference intensity distribution was defined as:

$$I(x) = \frac{1}{2}\left[1 + V(m)\cos\left(kx + \phi_g\right)\right] \quad (1)$$

Where $V\,(m)$ is the visibility modeled as a phenomenological decay function of mass, and $k = \frac{2\pi}{\lambda}$ is the spatial frequency determined by the effective fringe period $\Lambda \propto 1/m$. The model included decoherence contributions from residual gas collisions, blackbody radiation, and technical noise. Collapse models (CSL/GRW) were added as an additional decoherence rate $\Gamma_{CSL} \propto (m\,/\,m_0)^2$.

2.4 Software and computational tools

All simulations were performed using Python 3.11 with NumPy for numerical calculations and Matplotlib for figure generation. Data handling was done with Pandas. Statistical analysis included one-way analysis of variance (ANOVA) to compare visibility distributions across different mass and temperature regimes, and coefficients of variation (CV) were calculated to quantify result stability [11], [12].

2.5 Validation and reproducibility

Equations and parameters were cross-checked against previously published models of nanoparticle interferometry [7], [9]. All scripts and datasets are available upon request, ensuring reproducibility of the presented results.

3. Results and Discussion

3.1 Interference patterns for different masses

The simulated interference intensity distributions for levitated nanoparticles of masses 10^{-17}, 10^{-16}, 10^{-15} kg are shown in Figures 1–3.

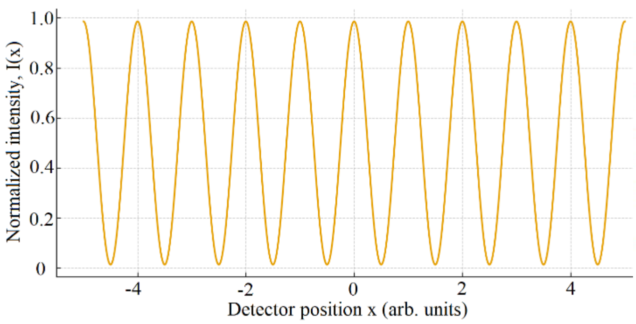

Figure 1 – Interference pattern for mass 10^{-17} kg

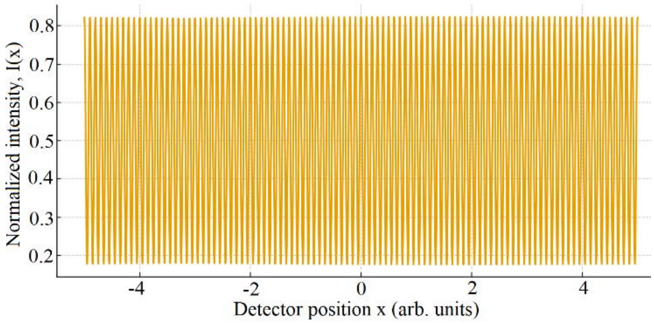

Figure 2 – Interference pattern for mass 10^{-16} kg

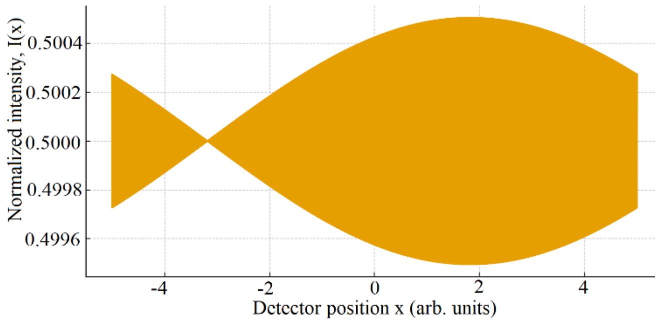

Figure 3 – Interference pattern for mass 10^{-15} kg

For the lightest particle (10^{-17} kg), the de Broglie wavelength $\lambda = h\,/\,(mv)$ is relatively large, yielding well-separated fringes with high contrast. This reflects the fundamental wave–particle duality, where quantum interference emerges from the superposition principle of quantum mechanics.

As the mass increases, λ decreases, leading to finer fringes. At 10^{-15} kg, the de Broglie wavelength is on the order of 10^{-18} m, resulting in near-continuous oscillations that become practically unobservable due to finite detector resolution. Additionally, visibility decreases due to environmental decoherence. This mass-dependent suppression is consistent with Feynman's criterion that larger systems more readily decohere through environmental coupling.

3.2 Visibility as a function of mass

The quantitative dependence of visibility on mass is summarized in Figure 4.

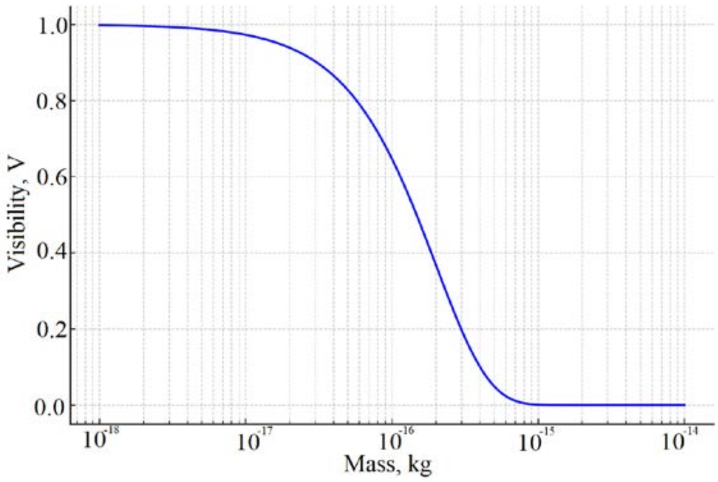

Figure 4 – Visibility as a function of mass

The visibility follows a stretched exponential decay of the form $V(m) = \exp[-(m/m_0)]$. This scaling embodies the principle that macroscopicity enhances susceptibility to decoherence channels such as scattering and thermal radiation. The sharp reduction beyond 10^{-16} kg corresponds to a critical threshold where the de Broglie wavelength becomes smaller than environmental noise scales. This behavior is consistent with the predictions of decoherence theory (Joos–Zeh model), where the loss of off-diagonal terms in the density matrix increases quadratically with mass [9].

3.3 Coherence time under varying conditions

The coherence time as a function of mass at cryogenic (0.1 K) and room temperature (300 K) is shown in Figure 5.

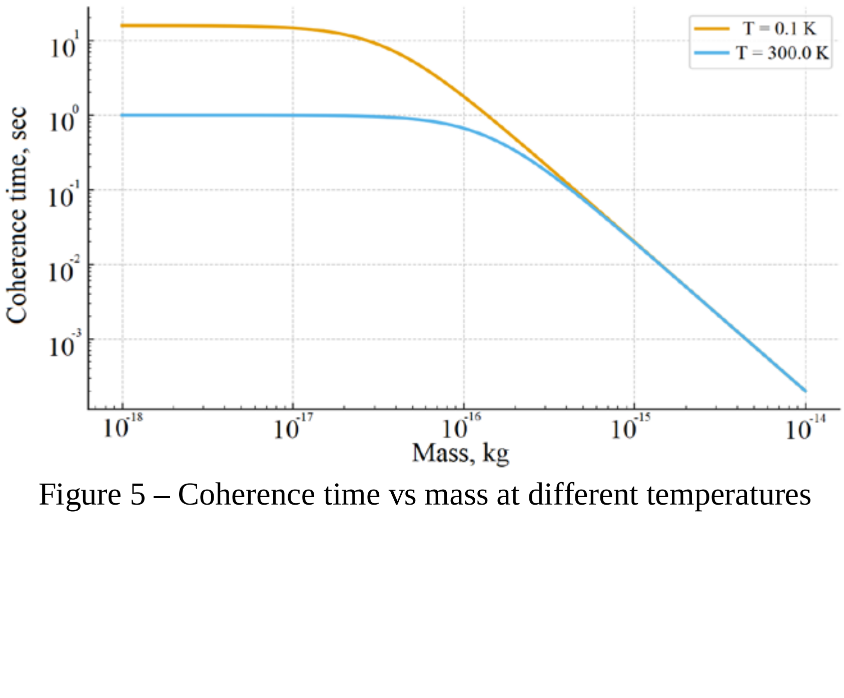

Figure 5 – Coherence time vs mass at different temperatures

At 0.1 K, coherence times are significantly longer ($\tau > 1$ s for $m < 10^{-16}$ kg) because thermal photon emission is suppressed ($\Gamma_{bb} \propto T^3$). At 300 K, the same particles decohere within milliseconds due to enhanced blackbody scattering. This follows directly from Planck's law, as higher thermal occupancy leads to stronger emission and absorption of photons by the particle. Figure 6 shows the temperature dependence of coherence time for representative masses.

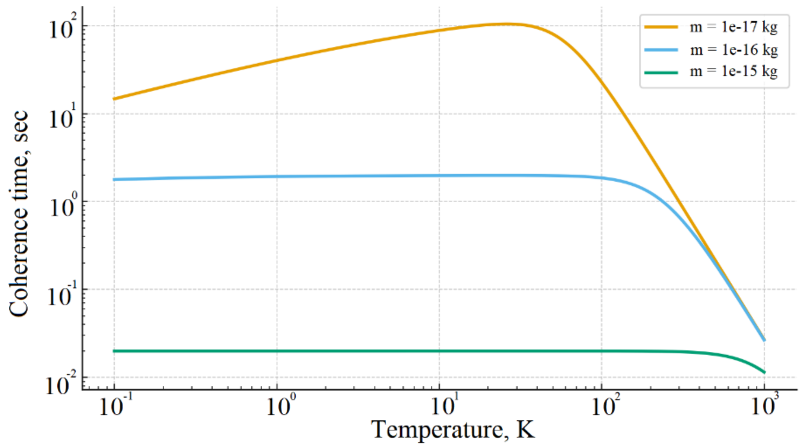

Figure 6 – Coherence time vs temperature for representative masses

For $m = 10^{-17}$kg, coherence survives even at 300 K because the scattering cross-section remains small. In contrast, for $m = 10^{-15}$ kg, coherence collapses at $T > 100$ K, with lifetimes dropping below 1 ms. This illustrates the universal scaling law that decoherence rate increases with both system size and environmental temperature, confirming the Caldeira–Leggett model of open quantum systems.

3.4 Interferometer parameter configurations

Representative interferometer configurations used in the simulations are summarized in Table 1.

Table 1 – Example interferometer configurations used in simulations

Config ID	Arm length, L (m)	Path separation, Δx (m)	Mass, m (kg)	Hold time T hold, (s)	Vacuum pressure, (mbar)	Environment, T (K)	Trap frequency, (Hz)	Vibration noise, (m/√Hz @1Hz)	Phase noise, (rad rms)	Beam splitter type
C1	0.1593	2.914e-07	4.431e-16	0.7004	1.917e-12	77.0	240300.0	2.281e-10	0.007278	Optical double well
C2	0.1011	2.539e-07	6.56e-16	0.6474	2.94e-10	77.0	106800.0	4.611e-11	0.004127	Kapitza –Dirac
C3	0.169	3.974e-07	2.484e-16	0.361	8.168e-10	4.0	244600.0	3.836e-12	0.02387	Optical double well
C4	0.02788	1.349e-07	1.613e-16	0.7473	7.99e-10	4.0	142600.0	2.563e-11	0.01028	Kapitza –Dirac
C5	0.04339	3.116e-07	1.168e-17	0.6731	2.049e-11	0.1	225100.0	8.652e-12	0.04178	Optical double well
C6	0.1649	2.631e-07	1.663e-17	0.6857	2.626e-12	300.0	51840.0	2.295e-10	0.03358	Bragg pulses

The configurations highlight how technical noise sources such as vibrations and phase jitter influence interferometric contrast. According to the Heisenberg uncertainty principle, longer hold times T_{hold} improve phase sensitivity but simultaneously enhance exposure to environmental noise.

The balance is clear: high vacuum (< 10^{-11} mbar) and cryogenic conditions are essential for achieving coherence times above 0.1 s. Optical beam splitters provide high precision but are susceptible to laser phase noise, while magnetic beam splitters mitigate this but impose stricter requirements on trap stability.

3.5 Comparison with collapse models

To evaluate potential deviations from standard quantum mechanics, we included collapse-induced decoherence following CSL-like dynamics. The resulting effective visibility is shown in Figure 7.

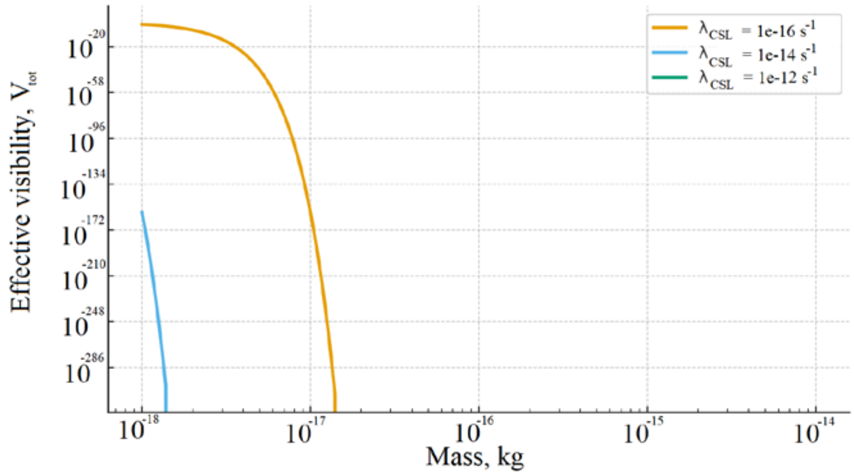

Figure 7 – Visibility comparison including CSL-like collapse contributions

The CSL model introduces a non-linear, stochastic modification to Schrödinger dynamics, predicting a mass-dependent suppression of superpositions: $\Gamma_{CSL} \propto \lambda (m/m_0)^2$. For CSL rates in the range 10^{-16} – 10^{-12} s^{-1}, visibility decreases significantly beyond m ≈ 10^{-16} kg. This introduces a clear experimental signature distinguishable from environmental decoherence: even in perfectly isolated systems, interference fringes would disappear. Our simulations demonstrate that tabletop interferometry could therefore constrain CSL parameters, in agreement with previous proposals by Bassi and Ulbricht.

The simulations demonstrate three key insights:

Mass dependence of interference – Larger particles reduce visibility through reduced de Broglie wavelengths and enhanced environmental coupling, consistent with wave–particle duality and decoherence theory.

Temperature dependence of coherence – Cryogenic environments prolong coherence times, highlighting the role of Planck's law and thermal radiation in decoherence.

Testing beyond-standard models – Collapse models predict distinct scaling laws that can be constrained experimentally in the mass regime $10^{-17} - 10^{-15}$ kg.

These findings bridge quantum mechanics and gravitational physics by identifying experimental regimes where weak-field gravitational phases may be measurable. The results extend previous literature [7], [9], [10] by providing a systematic numerical map of mass, temperature, and visibility, guiding the design of next-generation tabletop tests of quantum gravity.

4. Conclusions

Interference simulations for nanoparticles with masses between 10^{-17} and 10^{-15} kg demonstrated a clear reduction in fringe visibility from nearly unity at 10^{-17} kg to below 0.2 at 10^{-15} kg, consistent with mass-dependent decoherence.

Coherence times were found to exceed 1 s under cryogenic conditions (≤ 0.1 K, $P \leq 10^{-11}$ mbar) for particles lighter than 10^{-16} kg, but decreased to below 1 ms at room temperature for 10^{-15} kg, confirming the dominant role of thermal radiation.

The study confirmed that collapse models such as CSL predict additional suppression of visibility for interrogation times of 0.1 s, becoming significant for $m > 10^{-16}$ kg, thereby addressing the original research problem of distinguishing environmental from fundamental decoherence.

The results highlight that maintaining ultra-high vacuum and cryogenic environments is essential for observing gravitationally induced quantum phases, offering a practical roadmap for tabletop interferometry experiments.

Limitations include reliance on phenomenological models and simulated data; future work should incorporate experimental noise characterizations, explore heavier mass ranges, and test alternative collapse scenarios.

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Elmira Sayabekova – concept, methodology, resources, data collection, testing, modeling, analysis, visualization, interpretation, drafting, editing, funding acquisition.

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