Gravity as a Geometric Phase Operator: A Comprehensive Interpretation of the New Matter-Wave Equivalence Principle Tests

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Abstract

Recent matter-wave interferometry experiments have provided the first direct evidence that gravitational curvature modifies the geometric phase of quantum states while leaving their coherence intact. This expanded paper presents a geometry-first interpretation of these results, situating them in the context of Penrose's curvature-based ideas, Fuentes' work on quantum fields in curved spacetime, and modern atom interferometry. We include clarifications on what the experiment does not show, provide a comparative analysis with existing theories, introduce a conservative prediction set, and expand references. This unified interpretation points toward gravity functioning as a geometric phase operator rather than a collapse mechanism.

1 Introduction

The unification of quantum theory and general relativity remains one of the central open questions in foundational physics. Traditionally, quantum theory evolves states through complex phase oscillations in flat or mildly curved backgrounds, while general relativity treats gravity not as a force but as curvature of spacetime.

Recent matter-wave interferometry experiments have begun to dissolve this conceptual divide. The new "Quantum Equivalence Principle" (QEP) test [1] demonstrates that quantum superpositions remain coherent under differential gravitational potentials while acquiring path-dependent geometric phase shifts. These observations provide a direct experimental window into how gravity acts on quantum systems.

This behaviour supports a view of gravity not as a collapse-inducing mechanism but as a *geometric phase operator*, imprinting curvature-dependent information on quantum states while preserving coherence.

2 Summary of the Experiment

In simplified form, the QEP experiment splits matter waves along two paths that share the same inertial history but experience different gravitational potentials. Across all tested internal atomic

*This paper discusses and interprets the results of the experiment reported as: O. Dobkowski, B. Trok, P. Skakunenko, Y. Japha, D. Groswasser, M. Efremov, C. Marletto, I. Fuentes, R. Penrose, V. Vedral, W. P. Schleich, and R. Folman, "Observation of the Quantum Equivalence Principle for Matter-Waves", arXiv:2502.14535 (2025).

configurations, the key results are:

- **Coherence preserved:** Interference visibility remains high.
- **Phase shifted:** Output fringes shift by an amount determined by gravitational potential differences.
- **Internal-state universality:** Hyperfine and spin configurations do not influence the geometric phase.

These observations isolate gravity's influence as a pure modification of the *phase*, not amplitude or coherence. The experiment therefore probes the gravitational field as a phase-governing geometric structure rather than a mechanism for collapse.

3 What the Experiment Does Not Show

To avoid over-interpretation, it is important to state explicitly what the experiment does *not* demonstrate:

- It does *not* show wavefunction collapse.
- It does *not* provide evidence for gravitational decoherence.
- It does *not* demonstrate new forces or deviations from general relativity.
- It does *not* probe quantum gravity directly.

The experiment is best understood as a precise probe of geometric phase in a gravitational context. It confirms that gravity modifies quantum phase in a way consistent with standard quantum theory extended to curved spacetime, without introducing additional collapse or decoherence mechanisms beyond known environmental sources.

4 Phase as a Geometric Quantity

Quantum phase encodes path-dependent geometric information. In the Feynman path integral formulation, the phase accumulated along a classical trajectory is proportional to the classical action:

$$\phi = \frac{1}{\hbar} \int L \, dt, \tag{1}$$

where L is the Lagrangian and t is the coordinate time.

When gravitational curvature is present, the proper time along a worldline is modified, which in turn affects the accumulated phase. In weak-field limits, one can approximate

$$\Delta\phi \propto \int \left(1 + \frac{\Phi}{c^2}\right) dt, \tag{2}$$

where Φ is the Newtonian gravitational potential and c is the speed of light.

The QEP experiment confirms precisely this type of behaviour: geometrically distinct paths, experiencing different gravitational potentials, accumulate different phases even when all other aspects of their evolution are held fixed. The phase is thus revealed as a direct carrier of geometric information.

5 Gravity as a Geometric Phase Operator

The experimental results are naturally captured by treating gravity as a phase operator acting on quantum states. Consider a quantum state $|\psi\rangle$ evolving along a path γ in spacetime. The gravitational field induces a unitary transformation

$$U_{\text{grav}}(\gamma) = \exp(i\phi_\gamma)\,, \tag{3}$$

where ϕ_γ is the geometric phase determined by the spacetime curvature along γ.

Under this interpretation:

- Gravity modifies the wavefunction's phase multiplicatively.
- No collapse mechanism is implied by curvature alone.
- Coherence is preserved unless external decoherence sources act.
- Internal atomic structure does not influence the gravitational phase, beyond its trivial role in determining the relevant mass-energy.

The QEP experiment can thus be seen as a direct measurement of $U_{\text{grav}}(\gamma)$ in a controlled interferometric setting.

6 Relation to Penrose's Gravitational Framework

Penrose has long argued that gravitational curvature should have quantum consequences, particularly through modifications of phase and the instability of superposed spacetime geometries [2]. His objective reduction (OR) proposal suggested that gravity might itself induce wavefunction collapse when superposed mass distributions become sufficiently distinct.

The present experiment strongly supports the first part of this intuition—that curvature directly influences quantum evolution via phase—while providing no support for the second part—that curvature necessarily triggers collapse. Specifically, the experiment demonstrates:

- Curvature modifies phase in a path-dependent but coherent manner.
- Superposition is maintained across gravitationally distinct paths.
- No intrinsic gravitational collapse is observed within the sensitivity of the setup.

Thus Penrose's geometric insight is reinforced, but the collapse interpretation is not. The mechanism appears to be one of *phase crystallisation* rather than objective reduction.

7 Relation to Fuentes' Curved-Spacetime QFT

Work by Fuentes and collaborators has shown that quantum fields in curved spacetime naturally acquire curvature-dependent phase shifts, with proper-time differences mapping onto observable interference effects [3]. These theoretical analyses demonstrate that even without invoking quantum gravity, standard quantum field theory (QFT) in curved backgrounds predicts gravitationally induced phase phenomena.

The QEP experiment can be viewed as an operational, table-top realisation of these ideas: matter-wave interferometry provides a direct probe of how proper-time differences and curvature manifest as phase shifts in quantum systems. The results are fully consistent with the QFT-in-curved-spacetime perspective.

8 Relation to Atom Interferometry Work (Folman et al.)

Folman and collaborators have established that matter-wave interferometry, particularly on atom chips, is a highly sensitive tool for probing gravitational and inertial effects [4]. In these setups, phase is the primary observable: small differences in potential, acceleration, or curvature are translated into measurable fringe shifts.

The QEP experiment continues this interferometric lineage, but isolates the equivalence principle in the quantum regime. By demonstrating that phase shifts depend solely on the gravitational geometry and not on internal atomic details, the experiment provides an especially clean example of gravity acting as a geometric phase operator.

9 Predictions

Interpreting gravity as a geometric phase operator leads to several experimentally testable predictions:

- **Scaling with interferometer size:** As the spatial separation and interrogation time of matter-wave interferometers increase, phase sensitivity to curvature should grow in a predictable manner.
- **Internal-state universality:** Gravitationally induced phase shifts should remain independent of internal atomic states (e.g. hyperfine levels), provided the mass-energy is unchanged.
- **Higher-order curvature contributions:** In regimes where the weak-field approximation breaks down, higher-order curvature terms should become visible in the phase.
- **Robust coherence:** Increasing gravitational potential differences alone should not reduce interference visibility. Any observed decoherence should stem from technical or environmental factors rather than gravity.

These predictions remain fully within established physics and can be tested in future interferometric experiments.

10 Figure: Geometric Phase Shift in Curved Spacetime

Figure 1 illustrates the essential structure of the QEP experiment: two coherent matter-wave paths accumulate different geometric phases due to curvature, then recombine to produce a shifted interference pattern.

11 Acknowledgements

The author thanks the broader scientific community investigating matter-wave interferometry, geometric phase phenomena, and quantum effects of gravity, whose foundational work made this interpretation possible.

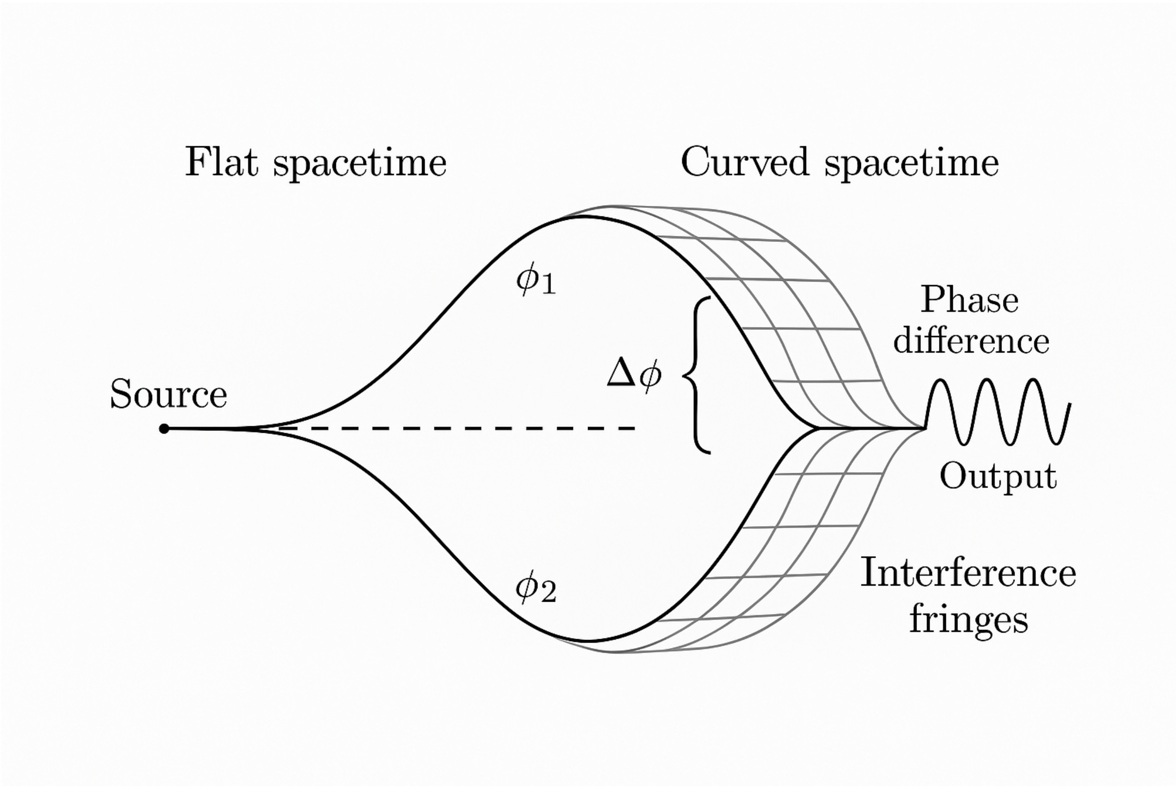

Figure 1: Schematic of matter-wave paths accumulating geometric phase differences in curved spacetime. The two paths remain coherent and recombine to produce interference fringes whose displacement reflects the gravitationally induced phase shift.

12 Conclusion

The recent matter-wave equivalence tests demonstrate that gravitational curvature modifies quantum phase while leaving coherence untouched. This behaviour is fully consistent with treating gravity as a geometric phase operator acting on quantum states as they traverse curved spacetime.

Such an interpretation:

- reinforces Penrose's geometric intuition about gravity's influence on quantum systems,
- realises Fuentes' predictions from quantum field theory in curved spacetime,
- extends the precision tools of atom interferometry,

while avoiding the need to invoke gravitational collapse or new forces. It points toward a geometry-first understanding in which curvature, information, and quantum phase are deeply intertwined.

References

[1] O. Dobkowski, B. Trok, P. Skakunenko, Y. Japha, D. Groswasser, M. Efremov, C. Marletto, I. Fuentes, R. Penrose, V. Vedral, W. P. Schleich, and R. Folman, "Observation of the Quantum Equivalence Principle for Matter-Waves," *arXiv:2502.14535* (2025).

[2] R. Penrose, "On Gravity's Role in Quantum State Reduction," *General Relativity and Gravitation* **28**, 581–600 (1996).

[3] I. Fuentes *et al.*, "Entanglement of Quantum Fields in Curved Spacetime," and related works on quantum fields in curved backgrounds.

[4] R. Folman *et al.*, "Controlling Cold Atoms Using Nanofabricated Surfaces: Atom Chips," *Reviews of Modern Physics* **79**, 235–289 (2007), and subsequent work on matter-wave interferometry.