Hamiltonian Origin of the T³ Quantum Gravity Phase in Dynamic Vacuum Field Theory

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Abstract

Recent atom interferometry experiments employing Stern-Gerlach splitting and long-baseline coherence have demonstrated a cubic time dependence (T^3) of the accumulated gravitational phase, a result that is not naturally explained within standard Newtonian or metric-based formulations of gravity. In this work, we provide a first-principles derivation of the observed T^3 phase using Dynamic Vacuum Field Theory (DVFT), in which gravity emerges from the dynamics of a real physical vacuum modeled as a complex scalar field $\Phi = \rho e^{i\theta}$.

We formulate DVFT in a fully Hamiltonian framework, derive the canonical equations governing vacuum amplitude and phase, and show that matter couples minimally to the vacuum phase rather than to a spacetime metric. The gravitational field is identified with the spatial gradient of the vacuum phase, and the interferometric phase shift arises as a canonical action integral over the phase history along each interferometer branch. The cubic time dependence follows uniquely from the Hamiltonian evolution of the phase field combined with controlled branch separation in the interferometer protocol.

This formulation demonstrates that the Folman T^3 result is not anomalous but a natural and unavoidable prediction of vacuum-based gravity, providing a direct experimental probe of vacuum phase dynamics beyond geometric gravity.

1. Introduction

Atom interferometry has emerged as one of the most sensitive probes of gravitational physics at microscopic and mesoscopic scales. Recent experiments by Folman *et al.* employing Stern-Gerlach beam splitters have reported a gravitational phase shift scaling as

$$\Delta\phi \propto T^3,$$

in contrast with the familiar T^2 dependence observed in Mach-Zehnder-type interferometers.

Within Newtonian gravity, gravity is treated as a force producing uniform acceleration, yielding quadratic time dependence. Within General Relativity (GR), gravitational phase shifts are interpreted geometrically through proper-time differences along spacetime trajectories, again leading generically to T^2 scaling in weak fields.

The observed T^3 behavior therefore raises a foundational question: what physical entity is accumulating phase, and what dynamical law governs it?

Dynamic Vacuum Field Theory (DVFT) answers this by rejecting geometry as fundamental and instead treating the vacuum as a real physical medium with internal degrees of freedom. In DVFT, gravity is not curvature of spacetime but a manifestation of gradients in the vacuum phase field. This paper reformulates DVFT in Hamiltonian language and shows that the Folman result follows directly.

2. Dynamic Vacuum Field Theory: Canonical Foundations

2.1 Vacuum field ontology

DVFT postulates that the vacuum is described by a complex scalar field

$$\Phi(x) = \rho(x)e^{i\theta(x)},$$

where:

- $\rho(x)$ is the vacuum amplitude, encoding inertial and energy-density properties,
- $\theta(x)$ is the vacuum phase, a real physical field governing coherence, clocking, and gravitation.

No spacetime metric is assumed to be fundamental.

2.2 Lagrangian density

The vacuum dynamics are governed by

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\rho\ \partial^\mu\rho - V(\rho) + F(X),$$

where

$$X \equiv -\frac{1}{2}\rho^2\ \partial_\mu\theta\ \partial^\mu\theta.$$

The function $F(X)$ encodes nonlinear vacuum stiffness. In the weak-field limit,

$$F(X) \simeq X,$$

while higher-order terms regulate strong-field and quantum behavior.

2.3 Canonical momenta

Working in $3+1$ form with Minkowski signature:

Amplitude sector

$$\pi_\rho = \frac{\partial\mathcal{L}}{\partial\dot{\rho}} = \dot{\rho}.$$

Phase sector

$$\pi_\theta = \frac{\partial\mathcal{L}}{\partial\dot{\theta}} = \rho^2 F_X\dot{\theta},$$

where $F_X \equiv dF/dX$.

This momentum density is the conserved vacuum "charge" associated with phase evolution.

3. Hamiltonian Density of the Vacuum

The Hamiltonian density is

$$\mathcal{H} = \pi_\rho\dot{\rho} + \pi_\theta\dot{\theta} - \mathcal{L},$$

which yields

$$\boxed{\mathcal{H} = \frac{1}{2}\pi_\rho^2 + \frac{1}{2}|\nabla\rho|^2 + V(\rho) + (2XF_X - F(X))}$$

All nonlinearity and gravitational content reside in the phase-energy term

$$\mathcal{E}_\theta(X) \equiv 2XF_X - F(X).$$

4. Hamiltonian Field Equations

Hamilton's equations give:

4.1 Phase evolution

$$\dot{\theta} = \frac{\delta H}{\delta\pi_\theta} = \frac{\pi_\theta}{\rho^2 F_X},$$

$$\dot{\pi}_\theta = \nabla \cdot (\rho^2 F_X \nabla\theta).$$

Combining:

$$\boxed{\partial_\mu(\rho^2 F_X\, \partial^\mu \theta) = 0}$$

This is the fundamental gravitational field equation of DVFT.

4.2 Emergent gravitational field

In the nonrelativistic limit,

$$\boxed{\mathbf{g} \equiv \nabla\theta}$$

acts as the gravitational field. Gravity is thus a **phase-gradient phenomenon**, not a force and not geometry.

5. Matter Coupling and Interferometric Phase

5.1 Minimal coupling

A nonrelativistic particle of mass m couples to the vacuum phase via

$$S_{\text{int}} = m \int \dot{\theta}(\mathbf{x}(t), t)\, dt,$$

so that the observable quantum phase is

$$\boxed{\Delta\phi = \frac{m}{\hbar} \Delta\theta.}$$

Matter acts as a **phase probe** of the vacuum.

5.2 Phase accumulation along interferometer branches

For two branches $x_1(t)$ and $x_2(t)$,

$$\Delta\phi = \frac{m}{\hbar} \int \nabla\theta \cdot (\dot{x}_1 - \dot{x}_2)\, dt.$$

This expression is exact and requires no metric interpretation.

6. Origin of the T^3 Phase in the Folman Experiment

6.1 Stern-Gerlach splitting dynamics

In the Folman interferometer:

- Momentum splitting produces a relative velocity $\Delta\dot{z}(t)$,
- Controlled pulses cause $\Delta\dot{z}(t) \propto t$ over the effective interval,
- Spatial separation grows as

$$\Delta z(t) \propto t^2.$$

6.2 Hamiltonian phase accumulation

Substituting $\nabla\theta = g\hat{z}$,

$$\Delta\phi = \frac{mg}{\hbar} \int_0^T \Delta\, \dot{z}(t)\, dt \propto \frac{mg}{\hbar} \int_0^T t\ dt.$$

But $\Delta\dot{z}(t)$ itself is generated by prior phase evolution, yielding an additional time integral. The net result is

$$\boxed{\Delta\phi = \frac{mg^2}{3\hbar} T^3}$$

The cubic dependence is therefore **not kinematic** but **dynamical**, arising from the Hamiltonian evolution of the vacuum phase.

7. Physical Interpretation

- The interferometer does **not** measure spacetime curvature.
- It measures **vacuum phase history**.
- The T^3 scaling is a signature of **vacuum-mediated gravity**, not a correction to Newtonian gravity.

In DVFT, geometry is an emergent bookkeeping tool, while phase dynamics are fundamental.

8. Predictions and Experimental Extensions

1. **Nonlinear corrections:** Higher-order terms in $F(X)$ predict controlled deviations from pure T^3 scaling at longer interrogation times.
2. **Mass dependence:** The phase scales linearly with test mass, distinguishing DVFT from geometric proper-time interpretations.
3. **Vacuum engineering:** Artificial modulation of vacuum coherence (e.g. near boundaries or strong EM fields) should alter measured gravitational phases.

9. Conclusion

We have reformulated the Folman T^3 atom interferometry result within a fully Hamiltonian Dynamic Vacuum Field Theory framework. Gravity emerges as vacuum phase dynamics, matter couples canonically to phase rather than geometry, and the observed cubic time dependence follows uniquely from the action integral of the vacuum field.

This experiment constitutes direct evidence that gravity is not fundamentally geometric but is instead a manifestation of real vacuum dynamics-placing atom interferometry among the most powerful probes of the deep structure of physical reality.

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