Infrared Temporal Indeterminacy: A Framework for Low-Energy Quantum Time Fluctuations

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Abstract

We propose a theoretical framework wherein time becomes increasingly indeterminate at low energy scales, contrary to the conventional assumption that quantum uncertainties diminish with decreasing energy. By introducing an energy-dependent time fluctuation term into the time evolution operator and scalar field Lagrangian, we formulate a novel perspective that unifies features of quantum mechanics, field theory, and infrared gravity. We show how such an approach modifies temporal and spatial uncerta...

1 Introduction

The interplay between energy and time has long been fundamental to our understanding of quantum systems. The uncertainty principle, $\Delta E \Delta t \geq \hbar/2$, typically implies that higher precision in energy measurement comes at the cost of temporal resolution. This has usually been interpreted as suggesting that lower energy systems are temporally more stable. However, this conventional view assumes a background of well-defined classical time.

In this paper, we challenge that assumption by postulating that the effective resolution of time itself depends on the energy scale of the quantum system in question. Motivated by foundational work on generalized uncertainty principles (GUP) [1], operational limits to spacetime measurements [2, 3], and recent discussions of emergent spacetime from quantum fields [4], we explore a formalism where time becomes increasingly fuzzy as energy approaches zero.

The concept of energy-dependent temporal indeterminacy provides an intriguing infrared dual to UV completions of gravity, which often propose minimum measurable lengths or times at high energies. Our framework suggests that quantum time itself becomes unresolvable in the deep infrared, leading to a duality of uncertainty across scales.

2 Methodology and Mathematical Framework

2.1 Energy-Dependent Time Fluctuations

We begin with the postulate that the effective resolution of time T_{eff} experienced by a quantum system is inversely related to its energy:

$$T_{\text{eff}}(E) = \tau + \delta t(E) = \tau + \frac{\hbar\gamma}{E^\beta}, \tag{1}$$

where τ is the classical proper time, γ a coupling constant, and $\beta > 0$ a scaling exponent.

2.2 Modified Time Evolution Operator

Using this modified time, the evolution operator becomes:

$$U = e^{-iHT_{\text{eff}}/\hbar} = e^{-iH\tau/\hbar} \cdot e^{-i\gamma H/E^\beta}, \tag{2}$$

introducing a non-unitary correction that dominates at low energies.

2.3 Infrared-Corrected Lagrangian Formulation

We modify the scalar field Lagrangian to include energy-sensitive time dynamics:

$$\mathcal{L} = \frac{1}{2}(1+\phi(x))^2(\partial^0\psi)^2 - \frac{1}{2}(\nabla\psi)^2 - V(\psi), \tag{3}$$

where $\phi(x) = \hbar\gamma/[T_{00}(x)]^{\beta/2}$ and T_{00} is the local energy density.

2.4 Modified Commutation Relations

The temporal fluctuation modifies the energy-time uncertainty principle:

$$\Delta t \gtrsim \frac{\hbar}{E} + \frac{\hbar\gamma}{E^\beta}, \tag{4}$$

leading to increased uncertainty at low energies. Spatial uncertainty also scales accordingly:

$$\Delta x(E) = \frac{\hbar}{2\Delta p} + \alpha \cdot \frac{\hbar\gamma v}{E^\beta}. \tag{5}$$

2.5 Path Integral Formulation

Incorporating the modified Lagrangian into the path integral:

$$\langle\psi_f|\psi_i\rangle = \int \mathcal{D}\psi\, e^{iS[\psi]/\hbar}, \quad S[\psi] = \int d^4x\, \mathcal{L}, \tag{6}$$

reveals a non-uniform weighting in low-energy spacetime regions.

2.6 Lorentz and Gauge Symmetry Considerations

The modification softly breaks Lorentz symmetry in the IR, but recovers it as $E \to \infty$. Gauge invariance is preserved in the extended scalar electrodynamics Lagrangian:

$$\mathcal{L} = (1+\phi(x))^2|D_0\psi|^2 - |D_i\psi|^2 - m^2|\psi|^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \tag{7}$$

2.7 Experimental Constraints

The parameters γ and β can be constrained using atomic clocks, neutrino oscillation experiments, and quantum optics setups probing low-energy coherence.

3 Conclusion

We have presented a novel framework where time becomes inherently indeterminate at low energy scales. By modifying the time evolution operator and incorporating an energy-sensitive field into the Lagrangian, we provide a mathematical foundation for this hypothesis. The resulting model suggests testable deviations from standard QFT predictions in low-energy regimes and opens new avenues for understanding time as an emergent, energy-dependent quantity.

References

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