Spacetime as an Emergent Causal Structure: A Quantum Mechanical Perspective

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Article

Spacetime as an Emergent Causal Structure

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Abstract

The nature of time and the invariance of the speed of light C are among the most profound open questions in fundamental physics. This paper presents a unified framework: time and causality are not fundamental quantities but macroscopically effective concepts emerging from local quantum decoherence. The core hypothesis is that the rate of proper time flow is proportional to the local decoherence rate, and the speed of light corresponds to the maximum velocity at which classical decoherence causal relations can propagate. Starting from open quantum systems, we rigorously formulate this hypothesis, demonstrate the natural emergence of Lorentz invariance and the light-cone structure, and systematically explain the mechanism of time emergence in vacuum and at absolute zero, ensuring the framework's self-consistency under extreme conditions. We also show, through a simplified model, that the framework is consistent with gravitational time dilation in general relativity. Cosmological implications are further derived: in an accelerating expanding universe, causal isolation will drive the dynamics of time toward a standstill. This conceptually self-consistent, mathematically rigorous, and experimentally testable framework not only provides a unified picture for the quantum origin of spacetime but also offers an epistemological perspective on the emergent properties of time, determinism, and truth.

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1. Introduction

The origin of time and the invariance of the speed of light constitute a central puzzle bridging quantum mechanics and general relativity. Quantum mechanics treats time as an external classical parameter, while general relativity describes spacetime as a dynamical geometry. A self-consistent theory of quantum gravity demands an understanding of how spacetime and time emerge from more fundamental quantum structures.

Decoherence theory explains how the classical world arises from the interaction of a quantum system with its environment. This work proposes that proper time is not fundamental, but determined by the local quantum decoherence rate. Causality and the speed of light c emerge as properties of classical information propagation.

This work presents a working hypothesis and interpretive framework, aiming to establish a conceptually unified and testable theoretical picture, rather than to replace the full formalism of existing quantum mechanics and general relativity.

2. Rigorous Connection to Open Quantum Systems

The interaction between a system and its environment is described by the Lindblad master equation:dtdϱ^=−ℏi[H^,ϱ^]+∑γΓγ(L^γϱ^L^γ†−21{L^γ†L^γ,ϱ^}),where ϱ^ is the density matrix, H^ is the Hamiltonian, L^γ are Lindblad operators, and Γγ are the corresponding decoherence rates.

Define the local effective decoherence rate:Γ=T21,where T2 is the decoherence time.

The core hypothesis is:dτ=ζ·Γdt,i.e., the rate of proper time flow is proportional to the decoherence rate, with ζ a dimensionless constant of proportionality.

3. Emergent Causality and the Speed of Light

Consider two spatially separated quantum systems. The establishment of observable classical correlations between them must proceed through the exchange of decoherence information via the environment. Define the causal front as the maximum propagation range over which classical correlations are stably established. Its upper limit vcf is determined by decoherence dynamics.

In a Lorentz-invariant vacuum environment, this upper limit is a universal constant, identified as the speed of light:c=sup(vcf).Thus, the light-cone structure emerges naturally from decoherence causal dynamics.

4. Vacuum, Causal Background, and Standard Time

A natural objection arises: in an ideal vacuum seemingly "empty", where does decoherence originate? How does time emerge? Within this framework, this question finds a self-consistent answer: the vacuum is not absolute "nothingness", but a physical background that allows causal information to propagate stably at the speed of light c. The causal structure of spacetime itself provides a minimal decoherence rate Γ0, ensuring that time can exist even in matter-free vacuum.

This interpretation guarantees the internal self-consistency of the framework: time is omnipresent because it originates from the causal structure itself; and the vacuum is precisely the purest and most stable manifestation of this causal structure.

The framework's interpretation of time can also be naturally extended to the physical scenario of absolute zero (T=0). Absolute zero implies the vanishing of thermal motion in the system, and the environment no longer provides thermal fluctuations. In this limit, the thermal contribution to decoherence tends to zero, and the decoherence rate reduces to a minimal limit Γmin determined by the causal structure of spacetime itself. According to the core hypothesis, this implies that even at absolute zero, time does not cease, but flows at the slowest, most fundamental rate in the universe. More specifically, as temperature approaches absolute zero, thermal motion is strongly suppressed, and information exchange and propagation based on thermal fluctuations nearly cease, driving the decoherence rate toward Γmin. Consequently, local proper time flow becomes extremely slow, macroscopically manifesting as a phenomenon approaching "time freezing". However, since the causal structure of spacetime provides an ineliminable minimal decoherence, time never fully stops.

5. Compatibility with General Relativity: An Example of Gravitational Time Dilation

To demonstrate self-consistency with general relativity, assume the decoherence rate depends on the gravitational potential Φ as:Γ∝(1+c22Φ)−*α*.

Substituting into the core hypothesis dτ∝Γdt, we obtain:dτ∝(1+c22Φ)−*α*dt.

To match the weak-field gravitational time dilation of general relativity:dτ=1+c22Φdt,it suffices to take:*α*=−21.

The physical interpretation is: stronger gravity corresponds to a lower decoherence rate and thus slower proper time flow.

This shows that gravitational time dilation can be interpreted as the modulation of the local causal background (decoherence rate) by matter.

6. Cosmological Implications

6.1. Cosmic Expansion and the Evolution of Time Flow

This framework naturally reveals the impact of cosmic expansion on the rate of time flow. As the cosmological scale factor increases, the density of matter and radiation decreases, and spatial separations increase, diluting the density of global causal correlations. The effective processes supporting classical information exchange and decoherence correspondingly decrease, leading to a gradual reduction in the cosmic average decoherence rate $\langle\Gamma\rangle$ with cosmic expansion. According to the core hypothesis $d\tau \propto \Gamma$, this directly leads to a key implication: the cosmic rate of time flow is not constant, but gradually slows down as the universe expands.

The early universe, with its small volume and high density, featured dense causal connections and a high decoherence rate, resulting in faster time flow; the current universe, undergoing expansion, has a slower time flow compared to the early universe; if the universe continues to expand in the future, time flow will further decelerate.

6.2. Accelerated Expansion and Dynamical Quiescence

In an accelerating expanding universe dominated by dark energy, the cosmic event horizon will eventually causally isolate all spatial regions from one another. When regions can no longer exchange any information, the decoherence processes between systems are strongly suppressed. In the limit, $\Gamma \to 0$, leading to:$dtd\tau \to 0$.

Time tends to "stop" in a dynamical sense, and the universe enters a deeper state of dynamical quiescence beyond thermodynamic "heat death".

7. Theoretical Application: Implications for Black Hole Physics

This framework provides a microphysical picture rooted in quantum information dynamics for the general relativistic description of black holes. In general relativity, the event horizon is a classical causal boundary; this framework links this geometric concept to more fundamental dynamical processes.

We propose that the event horizon is the macroscopic manifestation of a spacetime region where the decoherence rate Γ approaches zero. In a strong gravitational field, the highly distorted spacetime geometry severely inhibits the ability of a system to exchange information with the external environment (or between different parts of the system) and establish classical causal correlations. As the event horizon is approached, the effective decoherence rate Γ drops sharply; at the horizon itself, $\Gamma \to 0$.

According to the core hypothesis $d\tau \propto \Gamma dt$, this implies:

1. Stagnation of time flow: At the event horizon, the proper time of an infalling object as perceived by an external observer tends to stop, fully consistent with the gravitational time dilation effect in general relativity.
2. Termination of causal correlations: For an object crossing the horizon, the process of establishing classical causal connections with the external universe ceases.
3. Reinterpretation of internal spacetime: Inside the horizon, since $\Gamma \approx 0$, the concept of time is highly degenerate or even invalid, and classical causal structure no longer applies.

This picture can be naturally connected to Hawking radiation: the extremely strong gravitational field near the horizon dramatically modulates quantum vacuum fluctuations, inducing weak decoherence processes supported by quantum tunneling, which macroscopically manifest as thermal radiation. This provides a possible microdynamical origin for black hole thermodynamics.

In summary, this framework does not negate the black hole geometry of general relativity, but provides a physical realization mechanism based on information dynamics and causal emergence.

8. Extensions, Challenges, and Future Directions

This work proposes a framework for the emergence of time based on quantum decoherence, whose internal logic naturally extends to multiple areas of fundamental physics, while also pointing to directions requiring further development and validation.

8.1. Extending Insights from the Framework

The core relation $d\tau \propto \Gamma dt$ directly links the proper time flow rate to the rate of establishing causal correlations, suggesting that time is not an a priori background but a dynamical quantity reflecting the causal structure of the universe. This line of thinking can provide a potential unified perspective on several foundational physics problems:

- **Microscopic origin of the arrow of time**: The irreversibility of time may be linked to the irreversibility of decoherence processes, providing a quantum dynamical foundation for understanding the arrow of time.
- **Evolutionary features of the early universe**: The dense causal correlations corresponding to the high matter density of the very early universe may correspond to a higher decoherence rate, offering an intrinsic scaling perspective for understanding early universe dynamics alternative to inflationary scenarios.
- **Cosmic expansion and time scaling evolution**: The dilution of causal correlations due to cosmic expansion may gradually reduce the cosmic average decoherence rate, thereby affecting the overall flow rate of cosmological time. This effect may provide a complementary dynamical dimension to understanding the observational features of cosmic expansion.
- **Information-dynamical understanding of gravitational time dilation**: The modulation of spacetime causal structure by gravitational fields may provide a more microscopic physical picture for the gravitational time dilation effect in general relativity.
- **Time behavior at extremely low temperatures**: As temperature approaches absolute zero, thermal decoherence mechanisms are significantly suppressed, and the time flow rate may approach a lower bound determined by the fundamental causal structure of spacetime, offering a potential new observational direction for low-temperature physics.
- **Dynamical interpretation of black hole horizons**: Black hole horizons can be understood as regions where decoherence processes are strongly suppressed, providing an information-dynamical description for reinterpreting black hole causal structure, black hole thermodynamics, and the information paradox.

8.2. Future Directions and Pathways to Validation

Developing the above insights into a complete, testable theory faces several key challenges:

- **Theoretical rigor**: Formulate a covariant, observable definition of the local decoherence rate Γ within the framework of quantum field theory in curved spacetime, and explore connections to holographic principles, causal sets, and other quantum gravity approaches.
- **Cosmological observation modeling**: Construct an evolutionary model for the cosmic average decoherence rate, and derive its potential effects on observables such as the cosmic microwave background and baryon acoustic oscillations.
- **Application to strong gravitational field systems**: Quantitatively analyze the coupling between decoherence effects and gravitational fields in compact astrophysical objects such as black holes and neutron stars, and search for possible observational signatures.
- **Quantum simulation experimental tests**: Design experiments using artificial quantum systems such as superconducting quantum circuits and optical lattices to simulate "effective time flow" under controlled decoherence, testing the core hypothesis $d\tau \propto \Gamma dt$ on experimental platforms.

9. Epistemological Implications

This framework understands time as a macroscopic product of quantum decoherence, implying that classical time, classical causality, and classical reality emerge collectively. This provides a unified epistemological perspective for understanding the boundary between quantum and classical, the formation of objective reality, and the physical basis of causality.

10. Conclusions

This paper presents a unified spacetime framework rooted in decoherence as the origin of time. The rate of proper time flow is proportional to the local decoherence rate, and both causal structure and the speed of light receive a microscopic interpretation in terms of quantum information. This framework remains self-consistent under a variety of extreme conditions, including vacuum, absolute zero, gravitational fields, cosmic expansion, and the strong gravitational fields of black holes, and is naturally compatible with the gravitational time dilation effect of general relativity.

The theory demonstrates that time is not an a priori background, but a dynamical product of quantum information forming classical reality through causal correlations. This picture offers a concise, unified, and testable new pathway for understanding the quantum nature of spacetime, the microscopic origin of gravity, and the underlying logic of cosmic dynamics.

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