On the Emergence of Spacetime and the Speed of Light from Sub-Planckian Actions: A Threshold Interpretation of $\hbar$ and c

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Abstract

We reinterpret the reduced Planck constant $\hbar$ not as the lower limit of physical law, but as the threshold of distinguishable interaction. Below this threshold, sub-$\hbar$ actions contribute to a smooth, continuous, and physically meaningful statistical substrate—out of which spacetime and the invariant speed c emerge. At or above the threshold, interactions become measurable, giving rise to quantum discreteness. This conceptual reinterpretation bridges quantum field theory and relativity, providing a fresh philosophical framework for understanding the quantum-to-classical transition and the emergence of relativistic invariance.

Keywords: Emergence, Planck Constant, Quantum Fluctuations, Threshold Physics, Spacetime, Invariant Speed

1 Introduction

The reduced Planck constant $\hbar$ is conventionally regarded as the boundary of meaningful physical description, e.g., through the uncertainty relation $\Delta E \Delta t \geq \hbar/2$ [1]. We propose the opposite: that physics below this threshold—i.e., in the regime of sub-$\hbar$ action values ($J_s < \hbar$)—remains physically significant, contributing to a smooth substrate from which both the spacetime continuum and the speed of light c statistically emerge.

This proposal does not claim new empirical predictions but rather a reinterpretation of existing principles. It remains fully consistent with quantum field theory (QFT) and general relativity (GR), while offering an interpretative bridge between them.

2 Sub-$\hbar$ Actions and Indistinguishability

In the path integral formulation of quantum mechanics [3], the amplitude for a process is given by

$$\mathcal{A} = \int \mathcal{D}x \, e^{iS[x]/\hbar}, \tag{1}$$

where $S[x]$ denotes the action along a path. Paths with action much larger than $\hbar$ contribute negligibly due to destructive interference. However, for virtual fluctuations in the vacuum, the effective action typically remains below $\hbar$, as constrained by the energy–time uncertainty: $\Delta t < \hbar/\Delta E$.

These sub-$\hbar$ processes are indistinguishable in terms of measurable outcomes and thus contribute not to discrete events but to a continuous background. They realize dynamics via smooth translation, as described by the unitary translation operator:

$$\hat{T}(a) = e^{-ia\hat{p}/\hbar}. \tag{2}$$

For sufficiently small Δp, these translations alter expectation values without inducing measurable change [4]. In Wick-rotated spacetime, such sub-$\hbar$ dynamics correspond to non-interacting (timeless) trajectories [5].

3 Emergence of c as a Physical Threshold

In the massless pre-Higgs phase of the Standard Model, Lorentz invariance imposes $E = pc$ for particles [2]. In this context, the speed of light emerges as a statistical threshold: the critical regime where sub-threshold virtual processes cancel, and null-like paths dominate the observable dynamics ($ds^2 = 0$) [6].

This threshold separates unmeasurable translation (virtual propagation) from observable, quantized exchange ($J_s \geq \hbar$). A photon, for which $\tau = 0$, may thus be viewed as a boundary manifestation of the sub-$\hbar$ background: a coherent excitation at the edge of distinguishability [7].

4 Spacetime as an Emergent Substrate

Spacetime appears continuous because it arises as a coarse-grained statistical average over a dense sea of indistinguishable, sub-threshold quantum fluctuations [9]. Just as thermodynamic variables emerge from molecular ensembles, geometric continuity reflects the collective behavior of unresolved virtual paths.

This notion is supported by modern quantum gravity approaches. In holographic duality, spacetime geometry emerges from information entanglement [10]. Similarly, in quantum-spacetime phenomenology, no clear Planck-scale discreteness has yet been observed [8]. Sub-$\hbar$ actions may thus act as the entanglement base—the minimal substrate that ensures macroscopic spacetime geometry.

5 Implications and Outlook

In this framework, $\hbar$ no longer demarcates the edge of physics but the point at which structure becomes resolvable. Below it, we find not randomness or undefinedness, but structured, unresolvable continuity. The speed of light c marks the propagation limit within this emergent substrate.

While sub-$\hbar$ actions are not directly observable, precision effects such as refined Casimir measurements might one day offer indirect access to their structure [11]. Further theoretical work could model statistical ensembles of such sub-threshold fluctuations in lattice QFT frameworks to derive effective propagation limits or emergent metrics.

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