

Unification of the Casimir Effect and Cosmic Microwave Background: A Fundamental Vacuum Theory

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1 Introduction

This work develops a novel theoretical description that interprets the microscopic Casimir effect and the macroscopic cosmic microwave background (CMB) as different manifestations of an underlying vacuum structure. By introducing a characteristic vacuum length scale L_ξ and a fundamental dimensionless coupling constant ξ , it is shown that both phenomena can be described by a unified theoretical framework.

The theory is based on the hypothesis of a granular spacetime with a minimal length scale $L_0 = \xi \cdot L_P$, at which all physical forces are fully effective. For distances $d > L_0$, only parts of these forces become visible through vacuum fluctuations, which is described by the $1/d^4$ dependence of the Casimir force. Due to the extremely small size of L_0 , direct experimental measurement is currently not possible, which is why the measurable scale L_ξ serves as a bridge between the fundamental spacetime structure and experimental observations. Gravity is interpreted as an emergent property of a time field, whereby cosmic effects such as the CMB can be explained without the assumption of dark energy or dark matter.

2 Theoretical Foundations

2.1 Fundamental Length Scales

The proposed framework defines a hierarchy of characteristic length scales:

$$L_0 = \xi \cdot L_P \tag{1}$$

$$L_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616 \times 10^{-35} \text{ m} \tag{2}$$

$$L_\xi = \text{characteristic vacuum length scale} \approx 100 \mu\text{m} \tag{3}$$

Here, L_0 represents the minimal length scale of a granular spacetime at which all vacuum fluctuations are fully effective, while L_ξ represents the emergent scale for measurable vacuum interactions.

2.2 The Coupling Constant ξ

The dimensionless coupling constant ξ is determined to be

$$\xi = \frac{4}{3} \times 10^{-4} = 1.333 \times 10^{-4} \quad (4)$$

This constant functions as a fundamental space parameter that links the granulation of spacetime at L_0 with measurable effects such as the Casimir effect and the CMB. It can be derived from a Lagrangian describing the dynamics of a time field.

3 The CMB-Vacuum Relationship

3.1 Basic Equation

The central relationship of the theory links the energy density of the cosmic microwave background with the characteristic vacuum length scale:

$$\rho_{\text{CMB}} = \frac{\xi \hbar c}{L_\xi^4} \quad (5)$$

This formula is dimensionally consistent, since

$$[\rho_{\text{CMB}}] = \frac{[1] \cdot [\hbar c]}{[L_\xi^4]} = \frac{\text{J m}}{\text{m}^4} = \text{J/m}^3 \quad (6)$$

3.2 Numerical Determination of L_ξ

With the experimentally determined CMB energy density $\rho_{\text{CMB}} = 4.17 \times 10^{-14} \text{ J/m}^3$, L_ξ can be calculated:

$$L_\xi^4 = \frac{\xi \hbar c}{\rho_{\text{CMB}}} \quad (7)$$

$$L_\xi^4 = \frac{1.333 \times 10^{-4} \times 3.162 \times 10^{-26} \text{ J m}}{4.17 \times 10^{-14} \text{ J/m}^3} \quad (8)$$

$$L_\xi^4 = 1.011 \times 10^{-16} \text{ m}^4 \quad (9)$$

$$L_\xi = 100 \mu\text{m} \quad (10)$$

4 Modified Casimir Theory

4.1 Extended Casimir Formula

The Casimir effect is described by the following modified formula:

$$|\rho_{\text{Casimir}}(d)| = \frac{\pi^2}{240\xi} \rho_{\text{CMB}} \left(\frac{L_\xi}{d} \right)^4 \quad (11)$$

where d denotes the distance between the Casimir plates.

4.2 Consistency with the Standard Casimir Formula

By substituting the CMB-vacuum relationship (5) into the modified Casimir formula (11):

$$|\rho_{\text{Casimir}}(d)| = \frac{\pi^2}{240\xi} \cdot \frac{\xi\hbar c}{L_\xi^4} \cdot \frac{L_\xi^4}{d^4} \quad (12)$$

$$= \frac{\pi^2\hbar c}{240d^4} \quad (13)$$

This exactly corresponds to the established standard Casimir formula and proves the mathematical consistency of the proposed theory.

5 Numerical Verification

5.1 Comparison Calculations

To verify the theoretical consistency, Casimir energy densities are calculated for various plate distances:

Distance d	$(L_\xi/d)^4$	ρ_{Casimir} (J/m ³)	ρ_{Casimir} (J/m ³)
1 μm	1.000×10^8	1.30×10^{-3}	1.30×10^{-3}
100 nm	1.000×10^{12}	1.30×10^1	1.30×10^1
10 nm	1.000×10^{16}	1.30×10^5	1.30×10^5

Table 1: Comparison of Casimir energy densities between standard formula and new theoretical description

The perfect agreement confirms the mathematical correctness of the developed theory.

6 Physical Interpretation

6.1 Multi-scale Vacuum Model

The developed theory implies a fundamental structure of the vacuum at different length scales:

1. **Sub-Planck level (L_0)**: Minimal length scale of granular spacetime at which all physical forces, including vacuum fluctuations, are fully effective.
2. **Planck threshold (L_P)**: Transition region between quantum gravity and classical spacetime geometry.
3. **Casimir manifestation (L_ξ)**: Emergent length scale for measurable vacuum interactions that forms a bridge to the CMB.
4. **Cosmic scale**: Large-scale vacuum signature through the CMB, explained by a time field from which gravity emerges.

6.2 Emergent Gravity

Gravity is interpreted as an emergent property of a time field ϕ , whose fluctuations at the scale L_0 create the spacetime structure. The coupling constant ξ determines the strength of these interactions, whereby cosmic effects such as the CMB can be explained without the assumption of dark energy or dark matter.

7 Summary

This work develops a novel theoretical description that interprets the Casimir effect and the cosmic microwave background as different manifestations of an underlying vacuum structure. By introducing a sub-Planck length scale $L_0 = \xi \cdot L_P \approx 2.155 \times 10^{-39}$ m and a characteristic vacuum length scale $L_\xi \approx 100$ μ m, both phenomena are described in a unified mathematical framework.

The theory is mathematically consistent, reproduces all established Casimir formulas exactly, and makes specific experimental predictions. The coupling constant ξ is a fundamental space parameter that can be derived from a Lagrangian with a time field. Gravity is interpreted as an emergent property of this time field, whereby cosmic effects can be explained without dark energy or dark matter.

References

- [1] Dhital and Mohideen, *Physics*, 2024, DOI: 10.1103/PhysRevLett.132.123601.
- [2] Xu et al., *Nature Nanotechnology*, 2022, DOI: 10.1038/s41565-021-01058-6.