Extending Landauer's Principle: Testing the Vacuum Contribution with Casimir-Embedded Interferometry

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Date: September 17, 2025

Abstract

Landauer's principle establishes a minimum energy cost for information erasure, $E_{min} = k_B T \ln(2)$ per bit, traditionally interpreted as heat dissipation. This thermodynamic framework becomes problematic in the quantum regime at $T \to 0$, where thermal contributions vanish yet information processing remains physically meaningful. We propose that the energetic cost of information processing comprises two components: a thermal term and a vacuum contribution, ΔE_{vac}, arising from zero-point fluctuations. To test this, we introduce interferometric experiments using Casimir-sensitive geometries (Fabry–Pérot and/or Mach–Zehnder interferometers), where information operations (measurement or erasure) correlate with modulations in Casimir forces or cavity resonances. Detecting such correlations would confirm the quantum vacuum as an active participant in information dynamics, extending Landauer's principle beyond classical thermodynamics.

1. Introduction

Landauer's principle posits that erasing one bit of information incurs a minimum energy cost of $k_B T \ln(2)$, dissipated as heat into the environment [1]. Experimental validations in classical and mesoscopic systems have confirmed this bound [2–4]. However, in the cryogenic limit ($T \to 0$), the thermal term approaches zero, suggesting that quantum information erasure could occur without energetic cost. This contradicts the expectation that irreversible processes carry a physical footprint.

We hypothesize that the energetic cost of information processing is more general, involving a contribution from quantum vacuum fluctuations, quantifiable through the Casimir effect [5]. This effect, arising from boundary-dependent zero-point energy, provides a natural framework to probe vacuum contributions to information dynamics. We propose experimental tests using Casimir-embedded interferometers to detect these contributions, potentially unifying thermodynamics, quantum information, and vacuum physics.

2. Generalized Landauer Bound

Landauer's principle is expressed as:

$$E_{Landauer} = k_B T \ln(2).$$

We extend this to include a vacuum contribution:

$$E_{info} = k_B T \ln(2) + \Delta E_{vac},$$

where ΔE_{vac} represents a transient energy exchange with the quantum vacuum due to information processing.

Key features of this extension:

- At high temperatures, the thermal term dominates, recovering Landauer's original bound.
- At $T \to 0$, ΔE_{vac} ensures a non-zero energetic cost, preserving the physicality of information processes.
- We propose that ΔE_{vac} arises from local alterations in vacuum mode boundary conditions during quantum measurement or erasure.

3. Phenomenological Model with Theoretical Basis

Consider a quantum operation (e.g., measurement or erasure) that changes the information content by ΔI bits. We model the vacuum contribution as:

$$\Delta E_{vac} = \kappa \cdot \Delta I,$$

where κ is an effective coupling constant (energy per bit) to be determined experimentally. The total energy cost is:

$$\Delta E_{total} = k_B T \ln(2) \cdot \Delta I + \kappa \cdot \Delta I.$$

At T -> 0:

Delta E_total ≈ kappa * Delta I.

To estimate kappa, consider a simplified quantum field theory model: a quantum operation (e.g., qubit collapse) locally modifies the boundary conditions of a scalar field in a Casimir cavity. The shift in zero-point energy due to a change in mode cutoff is approximated as:

Delta E_vac ≈ (hbar c / a) * delta n,

where a is the cavity separation, and delta n is the change in effective mode number due to the operation. For a single-bit operation, assuming delta n ~ 1, and a = 100 nm:

kappa ≈ hbar c / a ≈ 2 x 10^-18 J/bit.

This suggests a small but potentially detectable effect with modern sensors.

4. Experimental Proposal

4.1. General Strategy

We propose quantum information operations within Casimir-sensitive geometries, synchronizing measurement or erasure events with observations of vacuum observables (Casimir force or cavity resonance shifts).

4.2. Fabry–Pérot Casimir Cavity

Setup: Two parallel conducting plates form a Fabry–Pérot cavity and Casimir plates (separation a = 100 nm, area A = 10^-8 m^2). A qubit (e.g., superconducting qubit) is embedded in the cavity, prepared in a superposition state and subjected to measurement or erasure.

Protocol: Perform repeated cycles of state preparation, measurement, and erasure. Use a laser to probe cavity resonance frequency omega. Synchronize detection with information operations.

Prediction: Each operation induces Delta E_vac, causing:

- A transient shift in resonance frequency, Delta omega / omega ≈ Delta E_vac / E_cavity.

- A modulation in Casimir pressure:

P(a) = - (pi^2 hbar c) / (240 a^4),

with fractional change Delta P / P ~ 10^-6 for Delta E_vac ~ 10^-18 J.

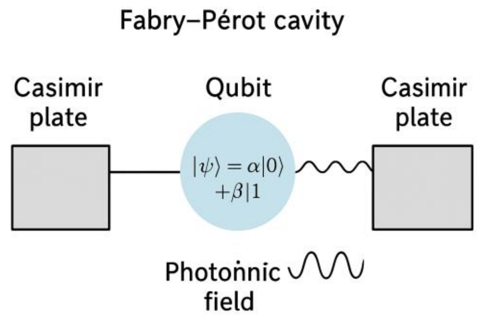

Figure 1: [Schematic: Fabry–Pérot cavity with two parallel Casimir plates. A qubit is embedded at the center. Arrows indicate laser input and resonance readout via a photodetector.]

4.3. Mach–Zehnder with Casimir Actuator

Setup: A Mach–Zehnder interferometer with one arm adjacent to a micro-cantilever acting as a Casimir plate (separation a = 100 nm from a fixed plate).

Protocol: Perform which-path measurements or erasure operations on photons in the interferometer. Monitor cantilever deflection using atomic force microscopy (AFM) techniques, synchronized with detector clicks.

Prediction: Information operations induce Delta E_vac, causing a transient Casimir force modulation, Delta F ~ 10^-15 N, detectable with state-of-the-art sensors [6–7].

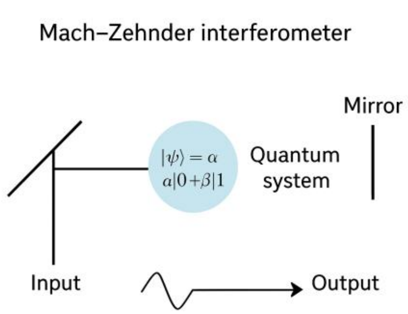

Figure 2: [Schematic: Mach–Zehnder interferometer with two arms. One arm is aligned near a micro-cantilever (Casimir actuator). An interference screen and synchronized photodetector record changes correlated with information operations.]

5. Detectability and Challenges

- Expected Signals: For a = 100 nm, A = 10^-8 m^2, the static Casimir force is F ≈ 10^-9 N. We expect Delta F / F ~ 10^-6, yielding Delta F ~ 10^-15 N, within reach of AFM sensors (resolution ~ 10^-18 N) [6–7].

- Signal-to-Noise: For N = 10^6 synchronized operations, the SNR scales as sqrt(N) ≈ 10^3, sufficient to detect Delta F.

- Controls: Use inactive detectors, randomized timing, and calibration against thermal and electromagnetic noise to isolate vacuum effects.

- Challenges: Requires precise synchronization and isolation from environmental noise. Numerical simulations (e.g., Monte Carlo) are recommended to optimize SNR.

6. Implications

A positive result would generalize Landauer's principle to include vacuum contributions, establishing information as a fundamental physical entity linked to zero-point energy. This has implications for:

- Quantum computing: Energy costs of error correction at cryogenic temperatures.

- Quantum gravity: Insights into vacuum fluctuations and information at Planck scales.

- Fundamental physics: Unifying thermodynamics and quantum vacuum dynamics.

A null result would set upper bounds on kappa, constraining the role of vacuum fluctuations in information processing.

7. Conclusion

We propose a falsifiable extension of Landauer's principle, incorporating a vacuum energy contribution to the cost of quantum information processing. Casimir-embedded interferometric experiments offer a feasible path to test this hypothesis, leveraging state-of-the-art sensors to detect correlated vacuum perturbations. Confirmation would reshape our

understanding of information's physical basis, bridging quantum information, thermodynamics, and vacuum physics.

References

[1] R. Landauer, IBM J. Res. Dev. 5, 183 (1961).

[2] A. Bérut et al., Nature 483, 187 (2012).

[3] Y. Jun et al., Phys. Rev. Lett. 113, 190601 (2014).

[4] J. Hong et al., Sci. Adv. 2, e1501492 (2016).

[5] H. B. G. Casimir, Proc. K. Ned. Akad. Wet. 51, 793 (1948).

[6] H. B. Chan et al., Science 291, 1941 (2001).