Dynamical Casimir Effect under parametric converter and amplifier

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Abstract— **The Dynamical Casimir Effect (DCE) arises from the conversion of vacuum fluctuations into real photons through time-dependent boundaries or parametric modulation. Here we study a quantum cavity mode with moving boundaries coupled to a detector mode (LC circuit), considering time-dependent couplings via parametric converters and amplifiers. Using the method of quantum invariants, we derive the quantum propagator, while the multiple-scale method in the weak-coupling regime provides the covariance matrix dynamics. We analyze entanglement, discord, squeezing, purity, Mandel factor, photon number, and distributions. Our results highlight how parametric modulation enhances photon production and quantum correlations in experimentally feasible scenarios.**

Keywords— **Dinamic Casimir Effect, Optomechanical Systems, Parametric Excitation.**

I. INTRODUÇÃO

The Dynamical Casimir Effect (DCE) involves the production of real photons from the quantum vacuum because of time-varying boundary conditions or changes in the attributes of a cavity, such as shifting mirrors or altered electromagnetic parameters [1,2]. This phenomenon occurs due to the parametric enhancement of vacuum fluctuations, transforming virtual photons into detectable photon pairs [3]. In setups with amplifiers and parametric converters, the DCE can be mimicked by adjusting the system's parameters to replicate the effect of shifting boundaries [4].

For example, in optical parametric amplifiers (OPAs), vacuum fluctuations can be squeezed, resulting in effects such as DCE [5]. By using lasers to pump non-linear crystals, one can design setups to mimic the transformations of fields reflected by oscillating mirrors, thus simulating the DCE within stationary systems. Similarly, in optomechanical systems, DCE can be implemented by driving a cavity mode parametrically to achieve squeezing, which is significant in quantum optics [6]. In such configurations, a mechanical oscillator can resonantly pair with the squeezed-cavity mode, enhancing the DCE in the squeezed reference frame. This strategy allows the DCE to be observed without requiring extremely high-frequency mechanical oscillations or stronger single-photon optomechanical interactions, making it experimentally feasible in various contexts.

Moreover, in superconducting circuits, the DCE has been demonstrated by quickly altering the boundary conditions of the electromagnetic field. In these environments, modulation can be tailored to enhance vacuum fluctuations, resulting in the generation of real photon pairs from the vacuum [7]. This technique offers a manageable framework for exploring vacuum amplification mechanics and their ties to parametric amplification processes. Thus, by using amplifiers and parametric converters, DCE can be accurately mimicked and scrutinized in various experimental frameworks, providing significant insight into quantum vacuum phenomena and the interactions between vacuum fluctuations and dynamic system parameters [8].

II. CONCLUSÕES

In this context, we consider one mode in a quantum cavity with moving boundaries coupled with another mode that works as an ideal detector (LC circuit). Unlike previous works with constant coupling [9], we introduce time-dependent couplings associated with both the parametric converter and the amplifier, focusing on their impact on photon production inside the cavity and on the detection process.

The dynamics are solved by applying the method of quantum invariants to obtain the quantum propagator [10], while the multiple-scale method [11] in the weak-coupling regime is employed to determine the time evolution of the covariance matrix for Gaussian initial states. The dynamical behavior of quantum correlations, such as entanglement and discord, is analyzed, along with quantum statistical properties of each mode, including squeezing, purity, Mandel factor, photon mean number, and photon distribution. This study provides new perspectives on the role of parametric modulation in photon generation and quantum correlations, contributing to a deeper understanding of experimentally accessible manifestations of the Dynamical Casimir Effect.

AGRADECIMENTOS

Ao programa de pós graduação em Física - UEPG. Ao grupo Quantum Physics and Quantum Information (QPQI). CAPES e CNPq.

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