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Dynamics of quantum resources under noisy spatial deformation of identical particles

A. Ferrara([1])([*]), F. Nosrati([1])([2])([3]), A. Smirne([4])([5]), J. Piilo([6]) and R. Lo Franco([1])

([1]) *Dipartimento di Ingegneria, Università degli Studi di Palermo - Viale delle Scienze, 90128 Palermo, Italy*
([2]) *IMDEA Networks Institute - Madrid, Spain*
([3]) *Nexus for Quantum Technologies, University of Ottawa - K1N 5N6, Ottawa, ON, Canada*
([4]) *Università degli Studi di Milano, Dipartimento di Fisica - Via Celoria 16, I-20133 Milan, Italy*
([5]) *Istituto Nazionale di Fisica Nucleare, Sezione di Milano - via Celoria 16, 20133 Milan, Italy*
([6]) *Department of Physics and Astronomy, University of Turku - FI-20014, Turun Yliopisto, Finland*

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Summary. — We present a microscopic derivation of a master equation for two bosonic qubits tunneling between spatially separated modes under local dephasing, described by a Lorentzian spectrum. The resulting time-local equation reveals intrinsic non-Markovian features. When the bath central frequency is resonant with the tunneling amplitude, dephasing can drive the system toward a correlated steady state that sustains coherence and entanglement, as opposed to complete decoherence predicted by white noise models. These results provide a rigorous foundation for pure dephasing in bosonic tunneling systems and demonstrate how structured noise can actively generate steady-state quantum correlations.

1. – Introduction

The coherent tunneling of identical particles between spatially separated modes lies at the heart of quantum interference phenomena, enabling effects such as bosonic bunching and serving as a resource for generating entanglement via spatial indistinguishability [1, 2]. In practice, such coherent processes are inevitably subject to decoherence. To model this interplay, open quantum system approaches are employed, often relying on phenomenological master equations that describe noise using simple, Markovian dissipators, effectively representing white-noise local dephasing. Such models usually predict

([*]) E-mail: alberto.ferrara@unipa.it

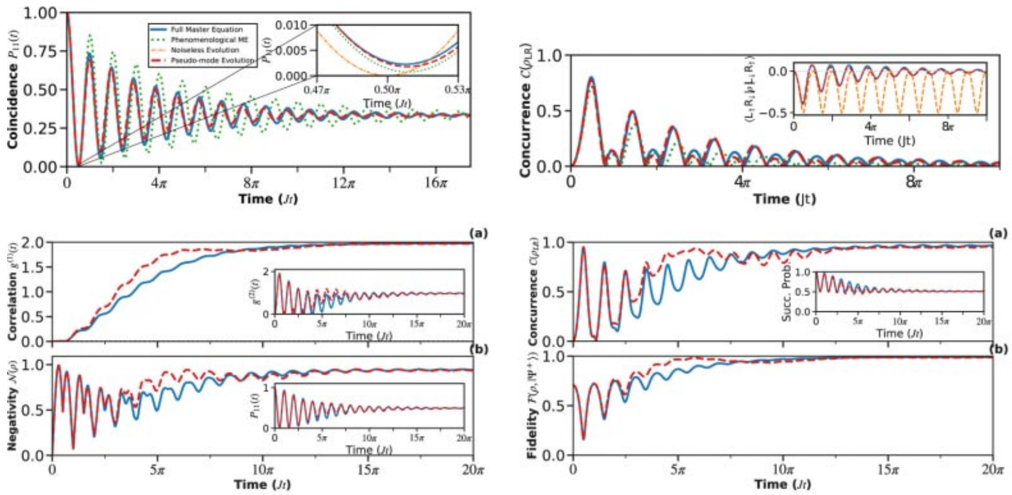

Fig. 1. – Top left panel: coincidence probability as a function of time for equal-spin bosons in the off resonance scenario. Bottom left panel (a): first and second order correlation functions on resonance for equal-spin bosons. Bottom left panel (b): entanglement negativity on resonance for equal-spin bosons. Top right panel: concurrence generated in the off resonance scenario for bosons with different spin. Bottom right panel (a): concurrence generated in the on resonance scenario for bosons with different spin and success probability of the protocol. Bottom right panel (b): fidelity of the generated state with the triplet state $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|\uparrow,\downarrow\rangle + |\downarrow,\uparrow\rangle)$.

irreversible suppression of coherence and entanglement, driving the system toward a classical mixture [3].

However, these phenomenological equations lack a direct microscopic foundation and may not capture the rich dynamics arising from structured environments. In this work, we derive a microscopic, time-local master equation for two bosonic qubits tunneling between two spatial regions coupled to local dephasing baths with a Lorentzian spectral density. We show that while the phenomenological limit is recovered at short times, the full colored model exhibits intrinsic non-Markovianity and reveals a resonant regime where dephasing no longer merely destroys coherence. When the bath's central frequency matches the tunneling rate, the noise cooperates with the coherent dynamics to stabilize steady-state quantum correlations and generate persistent mode entanglement.

2. – Model

We study a system made of two distinct spatial regions populated by particles following bosonic statistics. Each particle is characterized by a spatial degree of freedom and an internal pseudospin degree of freedom, admitting two distinct values. Within the no-label approach [1], a state vector describing a single particle with pseudospin σ localized in X can be expressed as $|\phi\rangle = |X\ \sigma\rangle$, where $X = \{L, R\}$ and $\sigma = \{\uparrow, \downarrow\}$. We define creation and annihilation operators $\hat{X}^\dagger_\sigma$ and $\hat{X}_\sigma$, creating or annihilating particles with a given pseudospin in a specific spatial region (*e.g.*, $\hat{L}^\dagger_\uparrow|0\rangle = |L\uparrow\rangle$, where $|0\rangle$ is a vacuum state). These operators obey bosonic commutation rules, $[\hat{X}_\sigma, \hat{X}^\dagger_{\sigma'}] = \delta_{\sigma,\sigma'}$, $[\hat{X}_\sigma, \hat{X}_{\sigma'}] = 0$, and $[\hat{X}^\dagger_\sigma, \hat{X}^\dagger_{\sigma'}] = 0$.

With $\hbar \equiv 1$, the free Hamiltonian of our system is $\hat{H}_S = \omega_s \sum_{X=\{L,R\},\ \sigma=\{\uparrow,\downarrow\}} \hat{n}_{X\sigma}$, where ω_s is the qubit transition frequency, equal for both particles, and $\hat{n}_{X\sigma} = \hat{X}_\sigma^\dagger \hat{X}_\sigma$ is the local number operator for a given pseudospin.

The bosonic qubits in the two spatial regions interact through a tunneling process

$$\hat{H}_D = \frac{J}{2} \sum_{\sigma=\{\uparrow,\downarrow\}} \left[\hat{L}_\sigma^\dagger \hat{R}_\sigma + \hat{R}_\sigma^\dagger \hat{L}_\sigma \right]. \tag{1}$$

The qubits interact locally with two independent zero-temperature bosonic baths, respectively. We consider two distinct bosonic baths, whose overall free Hamiltonian is $\hat{H}_E = \sum_{X=\{L,R\}} \int_0^\infty \omega\, \hat{b}_X^\dagger(\omega) \hat{b}_X(\omega) d\omega$, where $\hat{b}_X^\dagger(\omega)$ and $\hat{b}_X(\omega)$ are the bosonic creation and annihilation operators for mode with frequency ω in the bath localized at site X. The system-bath interaction Hamiltonian is defined as

$$\hat{H}_{SE} = \sum_{X=\{L,R\}} \left[\hat{\sigma}_{z,X} \otimes \int_0^\infty g_X(\omega) [\hat{b}_X(\omega) + \hat{b}_X^\dagger(\omega)] \mathrm{d}\omega \right], \tag{2}$$

where $\hat{\sigma}_{z,X} = \hat{n}_{X\uparrow} - \hat{n}_{X\downarrow} = \hat{X}_\uparrow^\dagger \hat{X}_\uparrow - \hat{X}_\downarrow^\dagger \hat{X}_\downarrow$. The system-bath coupling $g_X(\omega)$ is described by a spectral Lorentzian distribution $|g_X(\omega)|^2 = \frac{g_0}{\pi} \frac{\lambda}{(\omega-\omega_0)^2+\lambda^2}$, where λ is the spectral width and ω_0 is the central frequency of the bosonic bath mode, with g_0 setting the coupling strength. Following standard procedures for the derivation of a time-local Redfield equation (see ref. [4] or the derivation and the explicit form of the operators and coefficients), we obtain a master equation in canonical diagonal form:

$$\dot{\hat{\varrho}} = -i[\hat{H}_{\mathrm{can}}(t), \hat{\varrho}] + \sum_{i\in\{0,-,+\}} \gamma_i(t) \left[\hat{\mathcal{O}}_i(t) \hat{\varrho} \hat{\mathcal{O}}_i^\dagger(t) - \frac{1}{2} \{ \hat{\mathcal{O}}_i^\dagger(t) \hat{\mathcal{O}}_i(t), \hat{\varrho} \} \right]. \tag{3}$$

We analyze two-particle states, showing the resulting dynamical evolution, which is compared with numerical simulations of the full system-environment evolution, computed through the pseudomode method [5].

3. – Results

The derived master equation shows non-Markovian features [4], characterized by time-dependent decay rates $\gamma_i(t)$ with one eigenvalue $\gamma_-(t)$ remaining permanently negative. According to the phenomenological model, the dynamics shows a complete loss of coherence. For a structured Lorentzian bath, the long-time behavior depends critically on the resonance condition $\omega_0 \approx J$.

Equal-pseudospin bosons: Hong-Ou-Mandel interference. – For two bosons initially in the same pseudospin state, we monitor the coincidence probability $P_{11}(t)$. Off-resonance ($\omega_0 = 0$), dephasing suppresses the HOM dip and delays its occurrence, with the system eventually reaching a classical mixture (fig. 1 (top left)), consistent with white-noise expectations. On resonance ($\omega_0 = J$), tunneling is inhibited and the system evolves into a correlated steady state possessing non-zero coherence $C_s(t)$ and persistent mode entanglement, quantified by the entanglement negativity $\mathcal{N}(\hat{\rho}) > 0$ (fig. 1 (bottom left)).

Opposite-pseudospin bosons: entanglement distillation. – For bosons in opposite pseudospin states, the standard protocol for generating the Bell singlet $|\Psi_-\rangle$ via spatial deformation is analyzed [2,6]. Off-resonance, noisy tunneling generates transient entanglement concurrence near $Jt = n\pi$, which ultimately decays to zero (fig. 1 (top right)). In contrast, on resonance, the combined action of tunneling and dephasing drives the system to a steady state with high fidelity to the Bell triplet state $|\Psi_+\rangle$, maintaining substantial concurrence (fig. 1 (bottom right)).

4. – Conclusions

We derived a microscopic, time-local master equation for bosonic qubits tunneling between two spatial modes under the influence of local dephasing baths with a Lorentzian spectrum.

While the phenomenological model usually predicts the irreversible decay of coherence and entanglement, the microscopically derived equation reveals a resonant regime where the noise spectrum properties qualitatively change the steady state.

Our work opens several directions for future study, including extending the analysis to finite-temperature baths, common environments, and interacting many-body systems such as the full Bose-Hubbard model. It establishes a general framework for understanding the interplay between coherent tunneling and structured noise in open quantum platforms.

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