Dynamics beyond two-level approximation in transmon arrays

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Transmons are inherently quantum multilevel systems. Being experimentally controllable with high fidelity, the higher excited states beyond the qubit subspace provide an important resource for hardware-efficient many-body quantum simulations, quantum error correction, and quantum information protocols.

With the higher levels included, a transmon array realizes the attractive Bose-Hubbard model. The dynamics of the full model has been difficult to study both numerically and analytically due to the unfavourable scaling of the dimensionality of the Hilbert space with the system size. In this work [1, 2], we first present an analytic and numerical framework for describing the effective unitary dynamics of highly excited states based on high-order degenerate perturbation theory. This allows us to describe various collective phenomena—such as bosons stacked onto a single site behaving as a single particle, edge localization, and effective longer-range interactions—in a unified, compact, and accurate manner.

Dissipation and dephasing yield a practical limiting factor for the utilization of the higher-excited states. We show in detail the primary consequences of single-transmon dissipation and dephasing to the higher-excited state dynamics [3]. We use analytical methods from perturbation theory and quantum trajectory approach together with numerical simulations. The three main non-unitary processes are many-body decoherence, many-body dissipation, and heating/cooling transitions. Of these, the many-body decoherence gives the strictest limit for observing effective unitary dynamics. Our results show that state-of-the-art transmon arrays should be ready for demonstrating coherent many-body dynamics using the higher excited states.

Furthermore, when a transmon array is in a waveguide, collective decay involving the higher-excited states yields stronger super/subradiance than with qubits [4].

Our results on the higher-excited state dynamics can help with the design of new qudit-based quantum protocols and enable transmon arrays to be used to explore additional lattice models besides the standard Bose-Hubbard one.

References

[1] O. Mansikkamäki, S. Laine, M. Silveri, Phys. Rev. B 103, L220202 (2021)

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[3] O. Busel et al., Phys. Rev. Research 5, 023121 (2023)

[4] T. Orell et al., Phys. Rev. A 105, 063701 (2022)

Figures

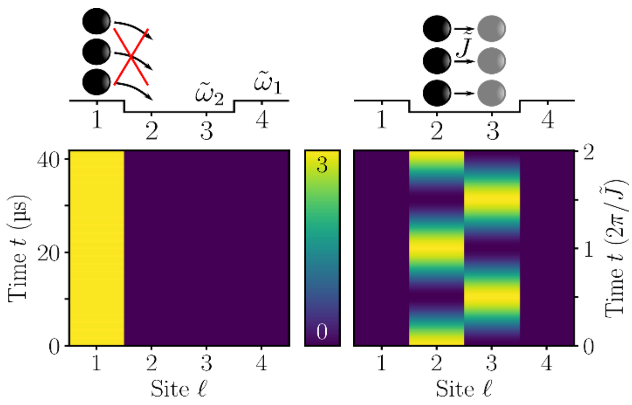

Figure 1: Schematic of boson stack localization and collective hopping in a transmon array.