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Harnessing Dynamical Symmetries for Coherent Control in Coupled Quantum Dot Systems

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Introduction

Quantum computing represents one of the most promising technological frontiers in modern physics and computer science, offering the potential to solve problems that are intractable for classical machines. Central to this revolutionary paradigm is the ability to control and manipulate quantum bits (qubits) with extreme precision and coherence. Among various qubit implementations, coupled quantum dot systems have emerged as a leading candidate due to their scalability, tunability, and compatibility with semiconductor fabrication technology. However, maintaining quantum coherence in such systems over usable timescales remains a profound challenge due to environmental decoherence and system noise. This issue motivates the exploration of deeper theoretical frameworks to control and stabilize the quantum dynamics involved. One promising approach lies in the construction and application of dynamical symmetries, which can fundamentally guide and constrain the evolution of quantum systems. Dynamical symmetries extend beyond mere conservation laws; they shape the entire trajectory of a system in Hilbert space, allowing for engineered robustness against certain types of perturbations and dissipation. This paper aims to investigate how the implementation of specific dynamical symmetries can enhance coherent control in coupled quantum dot systems, laying the foundation for fault-tolerant, efficient quantum computing architectures. By integrating algebraic techniques, group theory, and quantum control theory, we develop a framework that not only identifies the underlying symmetry structures in the quantum dot Hamiltonians but also demonstrates [1].

Description

The behavior of quantum dots semiconductor nanostructures that confine electrons or holes in discrete energy levels—mimics that of atoms, earning them the nickname “artificial atoms.” When two or more quantum dots are coupled through tunnel barriers or electrostatic interactions, they form artificial molecules capable of hosting and manipulating quantum information. The spin or charge degrees of freedom of electrons confined within these dots act as physical qubits. However, in practice, decoherence from phonon scattering, charge noise, and coupling to uncontrolled environmental degrees of freedom rapidly deteriorates quantum information. Addressing this requires a method of structuring and regulating the quantum evolution of these systems so as to suppress or compensate for these effects. This is where the concept of dynamical symmetry becomes highly relevant. Unlike static symmetries, which are associated with time-independent properties of the system such as parity or angular momentum conservation, dynamical symmetries are embedded in the full time evolution of the system. Mathematically, they can be described using Lie groups and Lie algebras whose generators commute or transform predictably with the system's Hamiltonian or time-evolution operator. For the SU(2) or SU(4) symmetry groups can be mapped to the spin states of single or coupled quantum dots. More generally, the framework of non-Abelian symmetries offers a high level of controllability through structured algebraic relations between quantum states and the operators acting on them [2].

In this work, we construct a theoretical model wherein the Hamiltonian of coupled quantum dots is embedded within a dynamical Lie algebra, and we demonstrate how time evolution under such symmetry-constrained Hamiltonians leads to stable and coherent dynamics. We begin by modeling the basic coupled quantum dot Hamiltonian with tunable inter-dot coupling, exchange interaction, and external control fields (magnetic or electric). We then identify symmetry conditions such as rotational invariance in spin space, time-reversal symmetry, and entanglement-preserving transformations that can be used to reduce the complexity of the system’s evolution. By applying algebraic diagonalization, symmetry-induced selection rules, and representation theory, we classify the quantum states into symmetry sectors, where transitions and decoherence are minimized. More practically, we simulate the time evolution of these systems under external pulsed fields and show how the presence of symmetry results in enhanced fidelity in quantum gate operations like the controlled-NOT (CNOT) gate, swap operations, and state superposition tasks. The application of dynamical decoupling sequences based on symmetry-aligned pulses also demonstrates significantly prolonged coherence times [3].

In the context of quantum control, we explore how symmetry-adapted control protocols such as bang-bang control, composite pulse sequences, and holonomic gates benefit from dynamical symmetry constraints. These protocols allow for error suppression without requiring full error correction, which remains a resource-intensive task. Furthermore, the formalism enables the design of geometrically protected qubits using topological aspects of the symmetry group, such as Berry phases and holonomies. These topological features are less sensitive to local noise, thereby offering an added layer of coherence protection. Experimentally, many of these predictions are testable using current quantum dot architectures, where control over tunneling rates, gate voltages, and external fields allows for precise tuning of the symmetry properties. For instance, recent advances in silicon-based quantum dot fabrication have shown the ability to preserve coherence over milliseconds under symmetry-protected pulse schemes. Our theoretical framework also provides a bridge to quantum simulation, where symmetry-guided dynamics can be simulated using cold atoms in optical lattices or trapped ions, offering a cross-platform validation of these ideas [4].

Another intriguing outcome of applying dynamical symmetry is the possibility of realizing quantum error-avoiding subspaces or decoherence-free subspaces in the coupled dot systems. These are special configurations of qubit states that remain invariant under specific environmental perturbations due to symmetry constraints. By embedding the physical qubits into these protected subspaces, we can effectively shield the system from certain classes of noise without needing active correction. Furthermore, we examine how entanglement dynamics evolve in the presence of dynamical symmetry. Entanglement central to quantum computation tends to be fragile under uncontrolled interactions. However, our simulations reveal that symmetry-preserving interactions lead to

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entanglement revival phenomena and long-range coherence that persists even under moderate levels of decoherence. These findings have strong implications for scalable quantum computing, where large arrays of coupled quantum dots may be operated under symmetry-governed protocols to achieve reliable quantum logic with limited resource overhead [5].

Conclusion

In conclusion, the development and utilization of dynamical symmetries in coupled quantum dot systems represents a significant advancement in the pursuit of stable, coherent quantum computation. By leveraging the algebraic and geometric structures provided by Lie group theory and symmetry analysis, we have demonstrated how these concepts can be systematically applied to control the evolution of quantum systems, enhance their coherence properties, and enable more robust quantum gate operations. Dynamical symmetries offer a powerful means of organizing the complexity inherent in coupled quantum dot Hamiltonians and provide a principled method for mitigating decoherence and operational errors. They serve not merely as mathematical artifacts but as active design principles that can be embedded in both theoretical models and experimental protocols. This symmetry-guided framework facilitates the realization of coherence-preserving subspaces, entanglement-protected operations, and noise-resistant qubit dynamics, all of which are essential for the implementation of scalable quantum computers. Furthermore, the approach harmonizes well with existing quantum control techniques and hardware capabilities, making it a practical and immediately applicable strategy.

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Conflict of Interest

No conflict of interest.

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