Usage Report for Fiscal Year 2024

Project Title:

Mobile spin qubit in magnetic domain wall racetrack

Name:
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1. Background and purpose of the project, relationship of the project with other projects

This project investigates the quantum properties of domain wall (DW) qubits in coupled quantum spin-1/2 chains using the Density Matrix Renormalization Group (DMRG) method. The goal is to establish a fully quantum framework for utilizing topological spin textures, such as domain walls, as qubits in scalable quantum architectures. Unlike previous semiclassical approaches, this work provides a rigorous quantum treatment, enabling the implementation of single- and two-qubit gates essential for universal quantum computation.

2. Specific usage status of the system and calculation method

The project employed the DMRG method, implemented via the ITensor Library, to study one-dimensional quantum systems. High-performance computing (HPC) resources were used to perform large-scale simulations, calculating ground-state energies, excitation gaps, and effective Hamiltonians for single and coupled DW qubits.

3. Result

Single DW Qubit: DMRG simulations showed that DWs with opposite chiralities form a well-defined low-energy sector, suitable for quantum information encoding. Qubit splitting is highly tunable via magnetic fields, characterized by anisotropic effective g-factors, enabling ultrafast single-qubit gates (1 ns).
Coupled DW Qubits: The interaction between two DWs in coupled spin chains was quantified, with the energy gap depending on inter-chain coupling strength. An effective Hamiltonian was constructed, enabling two-qubit gates. The interaction between moving DWs follows a Gaussian profile, with significant coupling occurring when DWs are within a distance comparable to their width. Position-dependent interactions between moving DWs were demonstrated, allowing for two-qubit gates with operation times as fast as 0.25 ns.

4. Conclusion

The project successfully demonstrated the feasibility of using DW qubits for universal quantum computation within a fully quantum framework. DMRG simulations provided a rigorous treatment of DW quantum properties, establishing a foundation for scalable quantum architectures based on topological spin textures. The tunability of qubit splittings and the ability to implement single- and two-qubit gates highlight the potential of DW qubits for practical quantum computing.

5. Schedule and prospect for the future

In the future, we plan to conduct time evolution simulations of quantum spin chains to model real-time gate operations.

Fiscal Year 2024 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

G. Qu, J. Zou, D. Loss and T. Hirosawa, Density matrix renormalization group study of domain wall qubits, arXiv:2412.11585 (2024)

[Oral presentation]

G. Qu, J. Zou, D. Loss, and T. Hirosawa, “Density Matrix Renormalization Group Study of Domain Wall Qubits,” APS March Meeting 2025, Anaheim, CA, USA.