Quantum simulation of 1D-fermionic systems with Ising Hamiltonians

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In recent years, programmable, analogue quantum simulators have become capable of simulating quantum critical phenomena in many-body systems, including dynamical phase transitions. However, many of these quantum simulations are focussed on Ising-type Hamiltonians with transverse fields, as these are native to quantum hardware platforms like superconducting flux qubits or neutral atoms. The simulation of 1D-systems of spinless fermions, or quantum spin chains, poses a challenge to these platforms due to the lack of non-stoquastic couplings.
We propose a method to simulate the time-evolution of certain spinless fermionic systems in 1D using simple Ising-type Hamiltonians with local transverse fields. Our method is based on domain-wall encoding [1], which is implemented via strong (anti-)ferromagnetic couplings |J|. We show that in the limit of strong |J|, the domain-walls behave like fermions in 1D. This approach makes the simulation of certain fermionic many-body systems accessible to contemporary analogue quantum hardware that natively implements Ising-type Hamiltonians with transverse fields.
As a proof-of-concept, we perform numerical simulations of various fermionic systems, such as the Aubry-Andre model, using domain-wall evolution and accurately reproduce various properties, such as phase diagrams and dynamical phase transitions.

References

[1] Nicholas Chancellor. Domain wall encoding of discrete variables for quantum annealing and QAOA. Quantum Sci. Technol. 4 045004 (2019)

Figures

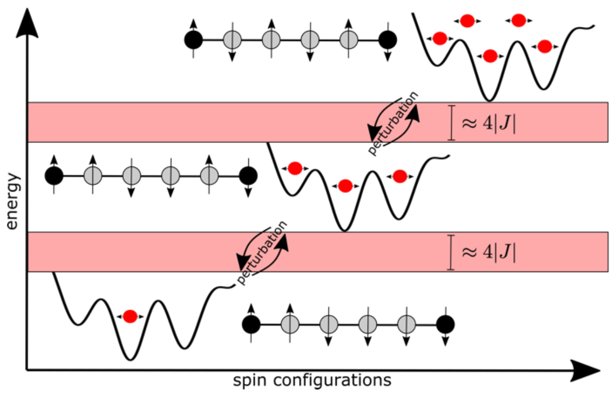

Figure 1: Illustration of the energy landscape of the domain-wall Hamiltonian. For sufficiently large |J|, the subspaces corresponding to different numbers of domain walls are separated by energy gaps of approx. 4|J| (red shaded areas). In each subspace, the domain-wall Hamiltonian is effectively a 1D-fermionic system, up to some perturbation due to off-diagonal matrix elements that vanish for large |J|.

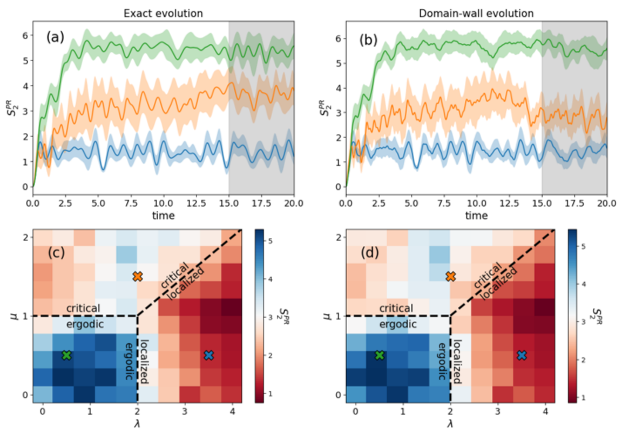

Figure 2: Time-evolution of the participation entropy S_2^{PR} (a, b) and MBL-phase diagram (c, d) of the Aubry-Andre model. The left plots (a,c) show the true quantities, while on the right (b,d) we see the approximation by domain-wall evolution. The blue, green and orange crosses in (c,d) correspond to the respective curves in (a,b)