

Phd Thesis Defense: Quantum simulation of lattice gauge theories with qudit systems

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10:30
Elements Room

The spectacular progress in controlling quantum matter has opened new avenues for studying fundamental physics. Various experimental platforms now host hundreds of quantum units, capable of quantum state engineering, Hamiltonian simulation and universal computation, already surpassing what is classically tractable. Remarkably, the versatility of such quantum simulators allows for investigating the physics from very high to very low energy scales.
While the long-term goal is to be able to perform fault-tolerant quantum computation, noisy intermediate scale quantum (NISQ) devices are prone to errors and quantum algorithms need to be tailored to the underlying physical platform by exploiting its advantages. In that regard, qudits offer enhanced Hilbert space dimension per information carrier with respect to qubits,

allowing for significant reduction of costly entanglement operations. Moreover, the higher-dimensional Hilbert space of qudits natively accommodates complex many-body models, thereby minimizing algorithmic overhead.
In this thesis, we investigate the opportunities that qudit devices offer for the quantum simulation of lattice gauge theories. Being extremely successful nonperturbative framework for studying three of the four fundamental interactions--electrodynamics, the weak and the strong force-- lattice gauge theories can be formulated as many-body systems amenable to quantum simulation. This approach overcomes the intrinsic bottlenecks of classical methods, unlocking the ability to explore out-of-equilibrium phenomena and finite-density equilibrium states.?

The first part of this thesis is dedicated to the development of encoding procedures fo lattice gauge theories with Abelian and non-Abelian symmetry on qudit quantum hardware Building upon advances in the understanding of the structure of the gauge-invariant Hilber space for specific symmetry groups, we propose scalable qudit implementation of gaug theory models in arbitrary spatial dimensions and devise variational protocols for thei equilibrium and out-of-equilibrium simulation. Crucially, our methods apply to gauge theorie with dynamical fermionic matter, without the need for nonlocal encodings for the fermions as they are unitarily removed in the encoding process

In the second part of this thesis, we use quantum-inspired numerical techniques to revea some of the plethora of physical phenomena simple many-body models with local symmetr host. Using the multi-flavour Schwinger model (quantum electrodynamics in one spatia dimension) as an example, we show how to identify signatures of fractons - gauge fiel configurations with fractional topological charge. Furthermore, by examining pure gaug theories with non-Abelian dihedral symmetry, we identify the importance of the centra subgroup for the spectrum and the dynamics of the many-body model, relating nontrivia fusion rules to lack of confinement and presence of exotic particle excitations. Mos importantly, the lattice gauge models for both examples above, due to their simplicity, ar amenable to near-term implementation on qudit quantum hardware

Ultimately, this work takes a significant step toward harnessing qudit quantum devices fo the simulation of high-energy and condensed-matter systems. By detailing resource-efficien hardware implementations and outlining near-term applications, our findings provid compelling motivation for the continued symbiosis of theoretical design and experimenta realization

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