Enhorabona al nou graduat de doctorat de l'ICFO

El Dr. Pavel Peychev Popov s'ha doctorat amb una tesi titulada ï¿½ Quantum simulation of lattice gauge theories with qudit systems"

May 29, 2026

Felicitem el Dr. Pavel Peychev Popov que ha defensat la seva tesi aquest mati a la sala elements de l'ICFO.
El Dr. Popov va obtenir el seu Master en Fisica per la Universitat de Heidelberg, abans d'incorporar-se al grup de recerca de Quantum Optics Theory dirigit pel professor ICREA d'ICFO el Dr. Maciej Lewenstein. La seva tesi titulada " Quantum simulation of lattice gauge theories with qudit systems" ha estat dirigida pel professor ICREA Dr. Maciej Lewenstein i el Dr. Valentin Kasper.

RESUM:

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 for 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 Hilbert space for specific symmetry groups, we propose scalable qudit implementation of gauge theory models in arbitrary spatial dimensions and devise variational protocols for their equilibrium and out-of-equilibrium simulation. Crucially, our methods apply to gauge theories 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 reveal some of the plethora of physical phenomena simple many-body models with local symmetry host. Using the multi-flavour Schwinger model (quantum electrodynamics in one spatial dimension) as an example, we show how to identify signatures of fractons - gauge field configurations with fractional topological charge. Furthermore, by examining pure gauge theories with non-Abelian dihedral symmetry, we identify the importance of the central subgroup for the spectrum and the dynamics of the many-body model, relating nontrivial fusion rules to lack of confinement and presence of exotic particle excitations. Most importantly, the lattice gauge models for both examples above, due to their simplicity, are amenable to near-term implementation on qudit quantum hardware.

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

realization.

Tribunal de Tesi:

Prof. Dr. Mari Carmen Banuls Polo, Max-Planck Institut für Quantenoptik

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? Prof. Dr. Hannes Pichler, Universitat Innsbruck