The Abdus Salam International Centre for Theoretical Physics

Workshop on Quantum Simulators of the Future: From Dynamical Gauge Fields to Lattice Gauge Theories | (SMR 3922)

20 Feb 2024 - 22 Feb 2024
ICTP, Trieste, Italy

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P01

Gauge-theoretic origin of Rydberg quantum spin liquids

P. S. Tarabunga[1,2,3], F. M. Surace[4], R. Andreoni[1,2,5], A. Angelone[6], and M. Dalmonte[1,2]

[1]*The Abdus Salam International Centre for Theoretical Physics (ICTP), strada Costiera 11, 34151 Trieste, Italy*
[2]*International School for Advanced Studies (SISSA), via Bonomea 265, 34136 Trieste, Italy*
[3]*INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*
[4]*Department of Physics and Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA*
[5]*Dipartimento di Fisica "G. Occhialini", Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, I - 20126 Milano, Italy*
[6]*Sorbonne Université, CNRS, Laboratoire de Physique Théorique de la Matière Condensée, LPTMC, F-75005 Paris, France*

Recent atomic physics experiments and numerical works have reported complementary signatures of the emergence of a topological quantum spin liquid in models with blockade interactions. However, the specific mechanism stabilizing such a phase remains unclear. Here, we introduce an exact relation between an Ising-Higgs lattice gauge theory on the kagome lattice and blockaded models on Ruby lattices. This relation elucidates the origin of previously observed topological spin liquids by directly linking the latter to a deconfined phase of a solvable gauge theory. By means of exact diagonalization and unbiased quantum Monte Carlo simulations, we show that the deconfined phases extend in a broad region of the parameter space; these states are characterized by a large ground state overlap with resonating valence bond wave functions. These blockaded models include both creation or annihilation and hopping dynamics, and can be experimentally realized with Rydberg-dressed atoms, offering novel and controllable platforms for the engineering and characterization of spin liquid states.

P02

Quantum simulation of discrete non-abelian Lattice Gauge Theories: error mitigation for a qudit-based quantum processor.

Edoardo Ballini[1,2], **Philipp Hauke**[1,2], **Emanuele Tirrito**[1,3], **Matteo Wauters**[1,2]

[1] *Pitaevskii BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy*
[2] *INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy*
[3] *ICTP, Strada Costiera 11, 34151 Trieste, Italy*

In the last years, our understanding of Quantum Simulation of Lattice Gauge Theories (LGTs) improved a lot. Nevertheless, there is still much to do, in particular because of the errors due to the NISQ era. In our work, we are trying to define a general framework to perform error mitigation for a non-Abelian, discrete, $2+1$ dimensions LGT. Our approaches are based on the Gauss's Laws, whose a general description for Abelian and non-Abelian groups can be found in [1], and which allows to define post-selection rules, as proposed for instance in [2] for an Abelian theory. Our work is also oriented to the qudit-based setup developed in [3].

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P03

Engineering lattice gauge theories with a Rydberg atom processor

J. Bergmann[1,2], **L. Tarruell**[2,3], **and A. Celi**[1]

[1]*Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*
[2]*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[3]*ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain*

Gauge theories are of utmost importance for our understanding of nature as they provide meaningful models to describe interactions between fundamental particles and striking phenomena like superconductivity and quantum spin liquids. To investigate the whole coupling regime of gauge theories like quantum chromodynamics it is crucial to develop new non-perturbative methods on the lattice that are not plagued by the sign problem like Quantum Monte Carlo simulations [1]. This search has determined a resurgence of the Hamiltonian approach to lattice gauge theory [2]. Quantum simulation with platforms like trapped ions or Rydberg atoms in reconfigurable optical tweezers are very well suited to implement such Hamiltonians as spin systems [1]. An important subject in this matter is the exploration of Ising models with S = 1/2 and higher in two and three dimensions [2]. As an example, I consider the well-known Rokhsar-Kivelson Hamiltonian, a 2D U(1) lattice gauge theory describing quantum dimer and spin-ice dynamics, in different geometries and investigate the resulting phase diagrams [3]. I explain how to engineer tunable anisotropic attractive as well as repulsive interactions with so-called superatoms by organizing two or more individual atoms in small clusters sharing one Rydberg excitation. The control of the couplings translates in blockade and antiblockade conditions arising in the dual formulation of the Rokhsar-Kivelson Hamiltonian [4]. In collaboration with the experimental group of Leticia Tarruell, I develop protocols to investigate this and other gauge theories with Rydberg atoms in reconfigurable optical tweezers. We choose this platform as flexible tweezers arrangements facilitate the investigation of different models and geometries in one, two and three dimensions. Furthermore, strong dipole interactions between Rydberg atoms are perfectly suited for simulating Ising-like interactions in spin models.

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[3] A. Browaeys, T. Lahaye, Nat. Phys. **16**, 132–142 (2020)
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In the last years, Rydberg atoms in reconfigurable optical tweezers proved to be an excellent platform to implement Spin-like Hamiltonians in ultracold atom experiments [1]. An important subject in this matter is the exploration of Ising models with S = 1/2 and higher in one, two and three dimensions, including the investigation of gauge theories emerging in condensed matter physics [2]. As an example, I consider the well-known Rokhsar-Kivelson Hamiltonian, a 2D U(1) lattice gauge theory describing quantum dimer and spin-ice dynamics, in different geometries and investigate the resulting phase diagrams[3]. I explain how to engineer tunable anisotropic attractive as well as repulsive interactions with so-called superatoms by organizing two or more individual atoms in small clusters sharing one Rydberg excitation. The control of the couplings translates in blockade and antiblockade conditions arising in the dual formulation of the Rokhsar-Kivelson Hamiltonian [4]. In collaboration with the experimental group of Leticia Tarruell, I develop protocols to investigate this and other gauge theories with Rydberg atoms in reconfigurable tweezer arrays.

[1] A. Browaeys, T. Lahaye, Nat. Phys. **16**, 132-142 (2020)
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P04

A study on the effect of ring exchange interaction in a two-leg Bose-Hubbard ladder

Sourav Biswas[1], **Enrique Rico Ortega**[1,2,3], **and Tobias Grass**[1,2]

[1] *Donostia International Physics Center, Donostia - San Sebastián, 20018, Spain*
[2] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*
[3] *EHU Quantum Center, University of the Basque Country UPV/EHU, P.O. Box 644, 48080 Bilbao, Spain*

In this work, we study the effect of ring exchange interaction in a two-leg Bose-Hubbard ladder using the DMRG (Density matrix renormalization group) technique. In realistic setups, a two-leg system is expected to be influenced by ring exchange [1, 2] mechanism apart from extended density-density interaction. In this regard, one can think of a two-band system and investigate different phases of matter emerging due to such interactions. The significance of such exchange terms has been known for a while [1, 2, 3]. In light of recent experimental observation [4] of the bose-metal phase, the study of such exchange interaction has become crucial for gaining more understanding of interacting bosonic systems.

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P05

Scaling of the quantum approximate optimization algorithm on superconducting qubit based hardware

Johannes Weidenfeller[1,2], **Lucia C. Valor**[1], **Julien Gacon,**[1,3] **Caroline Tornow**[1,2], **Luciano Bello**[1], **Stefan Woerner**[1], **Daniel J. Egger**[1]

[1]*IBM Quantum, IBM Research Europe – Zurich*
[2] *ETH Zurich*
[3] *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL)*

Quantum computers may provide good solutions to combinatorial optimization problems by leveraging the Quantum Approximate Optimization Algorithm (QAOA). The QAOA is often presented as an algorithm for noisy hardware. However, hardware constraints limit its applicability to problem instances that closely match the connectivity of the qubits. Furthermore, the QAOA must outpace classical solvers. In our work, we investigate and benchmark swap strategies used to map dense problems into linear, grid and heavy-hex coupling maps. Using known entropic arguments we find that the required gate fidelity for dense problems lies deep below the fault tolerant threshold. We also provide a methodology to reason about the execution-time of QAOA. Finally, we execute the closed-loop optimization on cloud-based quantum computers, using Qiskit Runtime, with transpiler settings optimized for QAOA. This work highlights some obstacles to improve to make QAOA competitive, such as gate fidelity, gate speed, and the large number of shots needed. The QAOA Qiskit Runtime program used acts as a tool to investigate such issues at scale on noisy superconducting qubit hardware.

P06

Efficient formulations of non-Abelian lattice gauge theories

P. Fontana[1] and A. Celi[1]

[1] *Departament de Física, Universitat Autónoma de Barcelona, E-08193 Bellaterra, Spain*

We show how to reformulate two-dimensional non-Abelian lattice gauge theories in terms of loop variables and conjugate loop electric fields, using canonical transformations on the initial degrees of freedom [1]. By explicitly solving the Gauss law on the lattice, we efficiently rewrite the Hamiltonian in terms of physical independent quantities, without any constraint left in the case of periodic boundary conditions [2]. This dualization procedure makes simpler the magnetic part of the Hamiltonian, introducing non-localities in the electric terms. We choose to work in the gauge group basis and, in the specific case of SU(2), propose a representation for the basis states allowing for an efficient covering of the group, without the introduction of finite non-Abelian subgroups. The combination with a proper truncation of angular momenta enables us to perform computations at arbitrary values of the bare coupling and lattice spacing, in a way to access regimes that are classically prohibitive [3].

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P07

Scaling concepts in and out of equilibrium

Giacomo Gori[1], **Andrea Trombettoni**[2], **and Tilman Enss** [1]

[1] *University of Heidelberg*
[2] *University of Trieste*

In some interesting many-body systems the collective behavior can be expressed in dramatic simplified way by introducing a space/time dependent length scale. The above scenario is exemplified with critical systems at equilibrium[1] and many-body quenches where the interaction is tuned to resonance[2].

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P08

Confinement in a one-dimensional $\mathbb{Z}_2$ lattice gauge theory at finite temperature

Matjaž Kebrič[1,2], Jad C. Halimeh[1,2], Ulrich Schollwöck[1,2], and Fabian Grusdt[1,2]

[1] *Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany*
[2] *Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany*

In our work we consider a one-dimensional $\mathbb{Z}_2$ lattice gauge theory (LGT), where dynamical charges are coupled to a $\mathbb{Z}_2$ gauge field defined on lattice links. In addition, we consider a $\mathbb{Z}_2$ counterpart of the Gauss law, which is a set of local operators that commute with the Hamiltonian. By choosing the so called physical sector without background charges, we obtain a physical picture where the $\mathbb{Z}_2$ electric field (also defined on the lattice links) changes its sign across an occupied lattice site. As a result, we consider that two particles (partons) are connected with a $\mathbb{Z}_2$ electric string, which reflects the orientation of the electric field.

For any non-zero value of the $\mathbb{Z}_2$ electric field term, which induces dynamics in the gauge fields, partons confine into dimers (mesons), since the electric field acts as a liner confining potential [1]. Confinement is probed by considering the $\mathbb{Z}_2$ invariant Green's function, which decays exponentially in the confined regime and with a power-law in the deconfined regime. The confinement problem in the ground state was solved by mapping the system to a non-local string-length basis, where confinement is related to translational-symmetry breaking in the new basis [2]. In addition, this system exhibits rich phase diagrams at different fillings [3].

We study the finite temperature properties of this LGT by using the concept of quantum purification, where we obtain finite-temperature states by performing imaginary time evolution on an enlarged lattice, where we attach an ancilla lattice site to every physical lattice site. By comparing the Green's function at different temperatures and fillings, for zero and non-zero electric field, we uncover a smooth confinement-deconfinement crossover [4]. By considering the Friedel's oscillations, which double in the confined regime, we show that mesons are preformed already at very high temperatures, relative to the hopping energy scale.

This LGT is already within reach of the current cold-atom setups. As a result, we also sample snapshots and extract string-length distributions, which we propose as a simple measure of confinement, which can be easily obtained in an experimental setup. Finally, we also show that mesons remain confined at finite temperature, by performing quench dynamics in smaller system sizes using exact diagonalization.

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P09

Probing stability of false vacuum with quantum quenches

Gianluca Lagnese[1], **Federica M. Surace**[2], **Sid Morampudi** [3], **and Frank Wilczek** [3,4,5,6]

[1]*(Presenting author underlined) Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*
[2] *Department of Physics and Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA*
[3] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4] *T. D. Lee Institute and Wilczek Quantum Center, SJTU, Shanghai*
[5] *Arizona State University, Tempe AZ USA*
[6] *Stockholm University Stockholm, Sweden*

Metastability is a state of equilibrium that is inherently unstable, yet persists over extended periods due to energy barriers hindering transitions to more stable configurations. It is a fascinating concept that pervades numerous scientific disciplines. Detecting whether a system is in a stable (true vacuum) or metastable state (false vacuum) is often a difficult task since the lifetime of a metastable state can be prohibitively long [1, 2]. Our work focuses on investigating vacuum stability through a genuine non-equilibrium real-time method [3]. We demonstrate that, by analysing in the Fourier space the time evolution after a quantum quench, we can differentiate between the two vacuums of the quantum transverse field Ising chain. The effect is observable at much shorter time scales than the typical time scale of the decay process. Inspired by the potential simulation of out-of-equilibrium dynamics in quantum field theories using atomic systems, we then show how, by tuning the parameters to the scaling limit, our results are consistently connected with the ones predicted by the field theory.

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P10

Percolation as a confinement (dis-)order parameter in $\mathbb{Z}_2$ lattice gauge theories

<u>Simon M. Linsel</u>[1,2], Annabelle Bohrdt[2,3,4,5], Lukas Homeier[1,2], Lode Pollet[1,2], and Fabian Grusdt[1,2]

[1]*Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, München D-80333, Germany*
[2]*Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*
[3]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[4]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[5]*Institute of Theoretical Physics, University of Regensburg, D-93053, Germany*

Lattice gauge theories (LGTs) were introduced in 1974 by Wilson to study quark confinement. These models have been shown to exhibit (de-)confined phases, yet it remains challenging to define experimentally feasible order parameters. Here we propose a percolation-inspired order parameter (POP) to probe confinement in $\mathbb{Z}_2$ LGTs with dynamical matter using electric field basis snapshots. We apply the POP to study a classical $\mathbb{Z}_2$ LGT and find a confining phase up to temperature $T = \infty$ in 2D (critical T_c in 3D) for any finite doping. Further, we demonstrate that the POP reproduces the square lattice Fradkin-Shenker phase diagram at $T = 0$ and explore the phase diagram at $T > 0$ using quantum Monte Carlo. While the critical field and the correlation length exponent coincide with the well-known 3D Ising universality class, the POP critical exponent is different ($\beta = 0.18(05)$). Our proposed POP is directly accessible to snapshots obtained in quantum simulators and suitable as a probe for quantum spin liquids.

P11

Higgs Portal to Dark Vector Physics

Natasha Mahmood[1], Muhammad Saad[1], and Dr. Tajdar Mufti[1]

[1] *Physics Department, Lahore University of Management Sciences(LUMS)*

The quantum field theories of the Higgs boson interacting with light vector particles offer a number of non-trivial features to study. Bound states, phase structure, dynamical mass generation, and the Higgs mechanism are among them. As light vector particles are dark matter candidates, a thorough understanding of the involved physics is crucial as experimental searches continue. It requires methods beyond perturbation theory to capture all aspects of the new physics. We present results from our ongoing study of a broken $U(1)$ gauge symmetry model containing $SU(2)$ invariant Higgs boson with a vector field. The method of lattice simulations is the choice for our investigation.

P12

We study an $SO(3)$ Quantum Link Model described by a Hamiltonian which is invariant under $SO(3)$ gauge group and study the embedding $so(6)$ algebra. The embedding algebra can be represented by t wo spinors per link. Using the bi-linear of spin operators we construct spin singlet and spin triplet at each site but because of Gauss's law constraints we checked only spin singlet state is gauge invariant. We did the exact diagonalization in $2+1$ dim for 2×2, 2×4, and, 4×4 lattices and computed the energy gap between ground state and excited states and see the spontaneous symmetry breaking of the translation symmetry. In addition, we study the VQE quantum algorithm for different lattice geometries (like two site lattice, triangular lattice, single plaquette) and compute their ground state energies.

P13

Quantum Simulator for phonon-assisted coherent transport of excitations in Rydberg-dressed atom arrays

Arkadiusz Kosior[1], Servaas Kokkelmans[2], Maciej Lewenstein[3,4], Jakub Zakrzewski[5,6] and Marcin Płodzień[4]

[1]*Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[2] *Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands*
[3] *Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*
[4] *ICREA, Passeig Lluis Companys 23, 08010 Barcelona, Spain*
[5] *Instytut Fizyki Teoretycznej, Uniwersytet Jagielloński, Łojasiewicza 11, 30-348 Kraków, Poland*
[6] *Mark Kac Center for Complex Systems Research, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland*

Polarons, which arise from the self-trapping interaction between electrons and lattice distortions in a solid, have been known and extensively investigated for nearly a century. Nevertheless, the study of polarons continues to be an active and evolving field, with ongoing advancements in both fundamental understanding and practical applications. Here, we present a microscopic model that exhibits a diverse range of dynamic behavior, arising from the intricate interplay between two excitation-phonon coupling terms. The derivation of the model is based on an experimentally feasible Rydberg-dressed system with dipole-dipole interactions, making it a promising candidate for realization in a Rydberg atoms quantum simulator. Remarkably, our analysis reveals a growing asymmetry in Bloch oscillations, leading to a macroscopic transport of non-spreading excitations under a constant force. Moreover, we compare the behavior of excitations, when coupled to either acoustic or optical phonons, and demonstrate the robustness of our findings against on-site random potential. Overall, this work contributes to the understanding of polaron dynamics with their potential applications in coherent quantum transport and offers valuable insights for research on Rydberg-based quantum systems [1].

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P14

Spin- and momentum-correlated atom pairs mediated by photon exchange and seeded by vacuum fluctuations

Nicola Reiter[1], **Fabian Finger**[1], **Rodrigo Rosa-Medina**[1], **Jacob Fricke**[1], **Panagiotis Christodoulou**[1], **Tobias Donner**[1], **and Tilman Esslinger**[1]

[1]*(Presenting author underlined) Institute for Quantum Electronics & Quantum Center, ETH Zürich, 8093 Zürich, Switzerland*

Engineering pairs of massive particles that are simultaneously correlated in their external and internal degrees of freedom is a major challenge, yet essential for advancing fundamental tests of physics and quantum technologies. In this work [1], we experimentally demonstrate a mechanism for generating pairs of atoms in well-defined spin and momentum modes. This mechanism couples atoms from a degenerate Bose gas via a superradiant photon-exchange process in an optical cavity, producing pairs via a single or two discernible channels. The scheme is independent of collisional interactions, fast and tunable. We observe a collectively enhanced production of pairs and probe inter-spin correlations in momentum space. We characterize the emergent pair statistics, and find that the observed dynamics is consistent with being primarily seeded by vacuum fluctuations in the corresponding atomic modes. Our results offer promising prospects for implementing lattice gauge theories in momentum space, in which the correlated pair dynamics preserve gauge invariance.

[1] Fabian Finger, Rodrigo Rosa-Medina, Nicola Reiter, Panagiotis Christodoulou, Tobias Donner, Tilman Esslinger, arXiv:2303.11326.

P15

Towards simulation of lattice gauge theories with ultracold ytterbium atoms in hybrid optical potentials

René Villela[1,2], **Tim Höhn**[1,2], **Etienne Staub**[1,2], **Leonardo Bezzo**[1,2], **Ronen Kroeze**[1,2] **and Monika Aidelsburger** [1,2,3]

[1] *Ludwig-Maximilians-Universität, München, Germany*
[2] *Munich Center for Quantum Science and Technology, München, Germany*
[3] *Max-Planck-Institut für Quantenoptik, Garching, Germany*

Gauge theories play a fundamental role in our understanding of nature, ranging from high-energy to condensed matter physics. Their formulation on a regularized periodic lattice geometry, so-called lattice gauge theories (LGTs), has proven invaluable for theoretical studies, as numerical studies on, e.g., their real-time dynamics are computationally challenging. We report progress on developing a quantum simulator for LGTs using neutral ytterbium atoms. Ytterbium's internal level structure provides a ground and meta-stable clock state pair, and fermionic isotopes further host nuclear spin degrees of freedom. We combine optical lattice and optical tweezer technology that can enable robust and scalable implementation of LGTs. To realize state-selective control, which is key for our approach to simulate LGTs[1], we exploit magic and tune-out wavelengths. We present the first measurements of such wavelengths near the narrow cooling transition at 556 nm [2] and discuss prospects in implementing local gauge invariance.

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P16

Two-dimensional $\mathbb{Z}_2$ lattice gauge theory on a near-term quantum simulator: variational quantum optimization, confinement and topological order.

Luca Lumia[1], **Pietro Torta**[1], **Glen B. Mbeng**[2], **Giuseppe E. Santoro**[1,3,4], **Elisa Ercolessi**[5], **Michele Burrello**[6], **Matteo M. Wauters**[6,7]

[1] *SISSA, Via Bonomea 265, I-34135 Trieste, Italy*
[2] *Universität Innsbruck, Technikerstraße 21 a, A-6020 Innsbruck, Austria,*
[3] *International Centre for Theoretical Physics (ICTP), P.O.Box 586, I-34014 Trieste, Italy*
[4] *CNR-IOM Democritos National Simulation Center, Via Bonomea 265, I-34136 Trieste, Italy*
[5] *Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, 40126 Bologna, Italy*
[6] *Niels Bohr International Academy and Center for Quantum Devices, Niels Bohr Institute, Copenhagen University, Jagtvej 155, 2200 Copenhagen, Denmark*
[7] *Pitaevskii BEC Center, Department of Physics, University of Trento, Via Sommarive 14, I-38123 Povo, Trento, Italy*

We propose an implementation of a two-dimensional lattice gauge theory model on a shallow quantum circuit, involving a number of single and two-qubits gates comparable to what can be achieved with present-day and near-future technologies. The ground state preparation is numerically analyzed on a small lattice with a variational quantum algorithm, which requires a small number of parameters to reach high fidelities and can be efficiently scaled up on larger systems. Despite the reduced size of the lattice we consider, a transition between confined and deconfined regimes can be detected by measuring expectation values of Wilson loop operators or the topological entropy. Moreover, if periodic boundary conditions are implemented, the same optimal solution is transferable among all four different topological sectors, without any need for further optimization on the variational parameters. Our work shows that variational quantum algorithms provide a useful technique to be added in the growing toolbox for digital simulations of lattice gauge theories.