QuaSIT | Quantum Science, Innovation and Technology

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Raccolta degli abstract

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Non-stabilizerness versus entanglement in matrix product states

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We investigate the relationship between entanglement and non-stabilizerness (also known as magic) in matrix product states (MPSs). We study the relation between magic and the bond dimension used to approximate the ground state of a many-body system in two different contexts: full state of magic and mutual magic (the non-stabilizer analogue of mutual information, thus free of boundary effects) of spin-1 anisotropic Heisenberg chains. Our results indicate that obtaining converged results for non-stabilizerness is typically considerably easier than entanglement. For full state magic at critical points and at sufficiently large volumes, we observe convergence with $1/\chi 2$, with χ being the MPS bond dimension. Mutual magic also shows a fast convergence with bond dimension, whose specific functional form is however hindered by sampling errors. As a by-product of our study, we show how Pauli-Markov chains (originally formulated to evaluate magic) resets the state of the art in terms of computing mutual information for MPS.

Title:

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Dephasing-tolerant quantum sensing for transverse magnetic fields with spin qudits

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We propose a protocol for quantum sensing of transverse magnetic fields which exploits spin qudits manipulated by longitudinal drives to obtain Rabi oscillations whose frequency is linear in the
transverse field to be probed. Decoherence affecting the system is overcome by exploiting the qudit multi-level structure to embed fault-tolerant quantum-error correction within the sensing protocol, thus making it robust against the most important noise source. The resulting protocol enables the detection of tiny transverse magnetic fields with remarkable sensitivity, as we demonstrate by numerical simulations.

Title:

Author:

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Strong Optomechanical Coupling with OAM in Cavities

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Optomechanical systems mediate interactions between optical and mechanical modes [1]. Thanks to this capability, they are very attractive for experiments in fundamental physics and the realization of optical sensors, interfaces, transducers and memory elements in classical and quantum regimes. We propose to exploit optomechanical coupling by using an ultra-low dissipation mechanical membrane [2], to realize transducers of linear and orbital angular momentum of light (Spin and OAM). In particular, the OAM is a very attractive degree of freedom due to its nature of infinite dimensionality. This unique peculiarity gives the possibility to transfer a wealth of information. We use the SAM-OAM converter q-plate, to produce light beams with OAM in our system due to the high generation efficiency and polarization control that provides this device [3,4] and that is required in systems at high laser power. The induced non-linear processes due to the high laser power must also be taken into account for the optomechanical coupling [5].
In our preliminary measurements in collaboration with CNR-IMEM, CNR-ISASI, FBK et UniNA, we obtained a frequency splitting for the mechanical modes, demonstrating that two spatial optical modes couple differently with the lower frequency and the higher frequency (M. Parisi et al. 2024 in preparation). In this activity, we aim to achieve optomechanical coupling in the quantum regime by using an ultra-low dissipation mechanical membrane in the middle of an optical cavity to achieve strong coupling. The optomechanical interaction Hamiltonian is of the form of the standard 'linearly' coupled optomechanical system

\begin{equation}
\hat{H} = - ihgx a^{†} a (b + b^{†})
\end{equation}

where a (a†) and b (b†) are the annihilation (creation) operators for the optical and mechanical modes respectively. The designed AOM-cavity apparatus can transfer through mechanical modes, the encoded information on optical beams with high fidelity [6]. The key element of this apparatus is an optical cavity with an ultra-low dissipation membrane in the middle. The cavity will be put in vacuum and at cryogenic temperature to minimize acoustic and thermal noise. The diagnostic systems will use interferometric techniques, high-resolution CCD cameras, and large-band detectors.

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Title:

Strong Optomechanical Coupling with OAM in Cavities

Author:

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Spontaneous Scattering of Raman Photons from Cavity-QED Systems in the Ultrastrong Coupling Regime

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We show that spontaneous Raman scattering of incident radiation can be observed in cavity- QED systems without external enhancement or coupling to any vibrational degree of freedom. Raman scattering processes can be evidenced as resonances in the emission spectrum, which become clearly visible as the cavity-QED system approaches the ultrastrong coupling regime. We provide a quantum mechanical description of the effect, and show that ultrastrong light- matter coupling is a necessary condition for the observation of Raman scattering. This effect, and its strong sensitivity to the system parameters, opens new avenues for the characterization of cavity QED setups and the generation of quantum states of light.

Title:

Spontaneous Scattering of Raman Photons from Cavity-QED Systems in the Ultrastrong Coupling Regime

Author:

Vincenzo Macri', Alberto Mercurio, Franco Nori, Salvatore Savasta, and Carlos Sánchez Muñoz

5

Closing Optical Bloch Equations in waveguide QED: Dynamics, Energetics

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Optical Bloch Equations (OBE) model the dynamics of driven-dissipative open quantum emitters. However from a global viewpoint, they derive from the evolution of closed and isolated emitter-field systems, where the fields comprise driving pulses and baths. Here we solve such a closed dynamics for an atom coupled to a field confined in one spatial dimension, a situation usually found in waveguide QED. Such closure of the OBE provides access to the atom-field correlations at all times. It unveils a new term capturing the driving of the atom onto itself, or self-drive, which is proportional to the atom coherences in the energy basis. The global energy of the closed system is conserved, such that energy exchanges between the atom and the field can be conveniently analyzed as closed first laws. Work-like (heat-like) flows stem from effective unitaries (correlations) exerted

by one system onto the other. We show that the closed and the open approaches differ by the atom self-work, yielding a tighter expression of the second law. We quantitatively relate this tightening to the extra knowledge acquired on the field state by closing the OBE.

Title:

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6

A simple method for measuring the quality of quantum computers

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We show that counting the number of collisions (re-sampled bitstrings) when measuring a random quantum circuit provides a practical benchmark for the quality of a quantum computer and a quantitative noise characterization method. We analytically estimate the difference in the expected number of collisions when sampling bitstrings from a pure random state and when sampling from the classical uniform distribution. We show that this quantity, if properly normalized, can be used as a "collision anomaly" benchmark or as a "collision volume" test which is similar to the well-known quantum volume test, with advantages (no classical computing cost) and disadvantages (high sampling cost). We also propose to count the number of cross-collisions between two independent quantum computers running the same random circuit in order to obtain a cross-validation test of the two devices.
A. Mari, arXiv:2312.04222 (2023).

Title:

Author:

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Quantum magic in permutationally invariant systems

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Nonstabilizerness, also known as quantum magic, quantifies the deviation of a quantum state from the set of stabilizer states and has emerged in recent years as an information-theoretic quantity to measure the true power of quantum computation beyond entanglement. Simulating and manipulating volume-law entangled quantum states with extensive magic is widely believed to pose considerable challenges for classical algorithms. Thus, numerical experiments have predominantly focused on systems with few qubits. Conventional methods for assessing the nonstabilizerness of an N-qubit system necessitate the computation of 4^N expectation values of Pauli strings over a state

with a dimension of 2^N. Permutationally invariant systems are the perfect playground to overcome this limitation. For permutationally invariant systems, the exponential computational overhead of computing the quantum magic can be significantly reduced to $O(N^3)$ expectation values on a state of dimension $O(N)$. This reduction allows exploring not only nonstabilizerness phase transitions in the ground states of this class of models but also across the entire many-body spectrum, paving the way to studying excited-state quantum phase transitions and magic dynamics in nonequilibrium (closed and open) settings in systems comprising hundreds of qubits.

Title:

Author:

8

Many-body quantum heat engines based on free-fermion systems

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We study the performances of an imperfect quantum many-body Otto engine based on free-fermion systems. Starting from the thermodynamic definitions of heat and work along ideal isothermal, adiabatic, and isochoric transformations, we generalize these expressions in the case when the hypotheses of ideality are relaxed (i.e., nonperfect thermalization with the external baths, as well as nonperfect quantum adiabaticity in the unitary dynamic protocols). These results are used to evaluate the work and the power delivered by an imperfect quantum many-body heat engine in a finite time, whose working substance is constituted by a quantum Ising chain in a transverse field: We discuss the emerging optimal working points as functions of the various model parameters.

Title:

Author:

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Multipartite Entanglement Engineering for Advanced Quantum Networks

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Entanglement is unanimously recognized as the key communication resource of the Quantum Internet. Specifically, entanglement enables a new form of connectivity, referred to as *entanglement-enabled* connectivity, which enables half-duplex unicast links between pairs of nodes sharing entanglement, regardless of their relative positions within the underlying physical network topology.

Thus, a shared entangled state gives birth to an overlay topology, i.e., an *artificial topology*, where pairs of nodes are connected via artificial links despite their physical proximity.

In this context, multipartite entanglement represents an unparalleled –yet widely unexplored – communication resource, which allows to decide at run-time the identities of the nodes interconnected within the artificial topology. Yet, the possibility of implementing novel network functionalities by exploiting the marvels of entanglement has been poorly investigated so far, by mainly restricting the attention to bipartite entanglement, such as EPR pairs. Conversely, with this workshop we aim at discussing how multipartite entanglement serves as *inter-network* resource. Specifically, we consider the interconnection of different *Quantum Local Area Networks* (QLANs), and we show that multipartite entanglement allows to dynamically generate an inter-QLAN artificial topology, by means of local operations only, that overcomes the limitations of the physical QLAN topologies. To this aim, we first discuss the design of the multipartite entangled state to be distributed within each QLAN. Then, we show how such a state can be engineered to: i) interconnect nodes belonging to different QLANs, and ii) dynamically adapt to different inter-QLAN traffic patterns. This contribution aims at providing the network engineering community with a hands-on guideline towards the concept of artificial topology and artificial neighborhood.

Title:

Multipartite Entanglement Engineering for Advanced Quantum Networks

Author:

Jessica Illiano, Marcello Caleffi and Angela Sara Cacciapuoti

10

Supersymmetry and Decoherence in the Phase Diagram of an Unconventional Superconducting Device

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Supersymmetry (SUSY) is a theoretical framework relating bosonic and fermionic space-time degrees of freedom extensively scrutinized in particle physics as an extension of the Standard Model. However, despite having the virtue of taming ultraviolet divergences and tackling hierarchy problems, no experimental evidence for SUSY partners has been found, suggesting that SUSY, if present in the space-time, must be realized only at very high energy scales. On the other hand, SUSY is not tied to space-time and can be realized and experimentally tested at low energy in condensed matter physics constructing unconventional quantum devices marking some relevant properties which emerge from the corresponding energy spectrum.
Here I present a novel device comprising two twisted cuprate Josephson junctions integrated in a Superconducting Quantum Interference Device (SQuID) loop and threaded by an external magnetic flux. The high-tunability of the device allows to explore various regimes with difference coherence properties hosting respectively: a symmetric, "twist-based", double-well potential, a "plasmonic" potential, and a "flux-biased"double-well potential. The possibility of realizing such an extensive phase diagram is related to the d-wave nature of the order parameter allowing peculiar symmetries on the Hamiltonian. They can be used to encode and significantly tune a topologically protected qubit called *flowermon* in the "twist-based"regime. Moreover, the emergence of a second non-trivial, "flux-biased", regime is granted by the opportunity of concretely realizing SUSY in the superconducting phase. SUSY shapes the energy spectrum with one non-degenerate ground-state and all other states degenerate in pairs and triggers sharp modifications in the system coupling to external noise fluctuations and, consequently, in the decoherence mechanisms.

Title:

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Time-dependent Hamiltonian reconstruction using continuous weak measurements

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Reconstructing the Hamiltonian of a quantum system is an essential task for characterizing and certifying quantum processors and simulators. Existing techniques either rely on projective measurements of the system before and after coherent time evolution and do not explicitly reconstruct the full time-dependent Hamiltonian or interrupt evolution for tomography. In this talk, I will introduce continuous weak measurements on quantum systems, coupled dispersively to microwave cavity and read using phase preserving or phase sensitive amplifiers. I will then describe an algorithm which recovers the Hamiltonian and density matrix from an incomplete set of continuous measurements, and demonstrate that it reliably extracts amplitudes of a variety of single-qubit and entangling two-qubit Hamiltonians. It will be further demonstrated how this technique reveals deviations from a theoretical control Hamiltonian, which would otherwise be missed by conventional techniques. Additionally, in contrast to previous work, this technique does not require interruptions, which would distort the recovered Hamiltonian.

Title:

Author:

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Local ergotropy: connection with quantum phase transitions and its "extended"version

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A fundamental problem in quantum thermodynamics is to properly quantify the work extractable from out-of-equilibrium systems. While for closed systems maximum quantum work extraction is defined in terms of the ergotropy functional, this question is unclear in systems interacting with an environment. First approaches towards schematizations of open quantum batteries involved the use of the Lindblad master equation, under Markovian and weak-coupling assumptions [1]. Later, in order to consider arbitrary Hamiltonian coupling, the concept of local ergotropy was proposed in [2] as the maximum extractable work from the system-environment compound by applying a local unitary on the system.
Being interested in potential connections with many-body phenomena beyond the Markov approximation [3], we investigate a two-qubit open Rabi model, focusing on local ergotropy, within a parameter regime where a Berezinskii-Kosterlitz-Thouless dissipative phase transition occurs [4]. We define a protocol for charging, storing in quasi-decoherence free subspaces, and discharging the two-qubit system, interpreted as the working principle of an open quantum battery. We further examine the impact of the phase transition on local ergotropy and identify potential markers based on it.
From a more fundamental point of view, we unfold formal weaknesses in the definition of local ergotropy, such as the fact that it is not guaranteed to be non-increasing in time [5]. We then introduce the concept of extended local ergotropy by exploiting the free-evolution of the system-environment

compound. At variance with the local ergotropy, the extended local ergotropy is greater by construction, is non-increasing in time, and activates the potential of work extraction in many cases. We provide examples based on the Jaynes-Cummings model, presenting practical protocols and analytic results that serve as proof of principle for the aforementioned advantages.

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[3] Di Bello, G., Farina, D., Jansen, D., Cataudella, V., Giovannetti, V., Perroni, C.A., De Filippis G., (2024), Local ergotropy and its fluctuations across a dissipative quantum phase transition. In preparation.
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Title:

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Evaluating Quantum Convolutional Neural Networks for Transient Gamma-Ray Burst Signal Detection

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Quantum Machine Learning (QML) merges Quantum Computing with Machine Learning to address complex problems in various scientific fields, including Astrophysics. Astrophysics, with its reliance on extensive datasets from terrestrial and satellite observations, demands rapid and precise methodologies for data analysis. Deep Learning (DL) has increasingly been applied to tackle astrophysical challenges, yet the potential of Quantum Deep Learning (QDL) remains underexplored.

This study focuses on the performance of Quantum Convolutional Neural Networks (QCNNs) in detecting transient Gamma-Ray Bursts (GRBs), which are intense, brief gamma-ray flashes originating from cosmological events. GRBs are categorized into short-duration bursts, resulting from neutron star mergers, and long-duration bursts, caused by the collapse of massive stars.

Building on prior work (Rizzo et al. 2024) demonstrating QCNNs' effectiveness in identifying GRBs in AGILE mission data, we expanded our analysis to include simulations from the Cherenkov Telescope Array (CTA). The CTA represents the next generation of ground-based observatories for high and very-high energy gamma-ray science, featuring advanced, sensitive telescopes and real-time data analysis capabilities crucial for immediate GRB detection and alert generation.

We employed hybrid quantum-classical machine learning techniques, using Parametrized Quantum Circuits, and evaluated the QCNN performance through both Pennylane and Qiskit libraries. Various architectures and encoding strategies, including Data Reuploading and Angle and Amplitude encoding, were explored.

Our comparative analysis with classical CNNs revealed that QCNNs achieved comparable accuracy (over 90%) with fewer parameters, although they did not yet surpass classical methods in terms of training time, due to the nascent state of quantum deep learning optimizations.

As the first exploration of QCNNs in astrophysical applications, this research highlights the potential, benefits, and current limitations of integrating quantum approaches in astrophysics, paving the way for future advancements in the field.

Title:

Author:

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Counterfactuality, back-action, and information gain in multi-path interferometers

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The presence of an absorber in one of the paths of an interferometer changes the output statistics of that interferometer in a fundamental manner. Since the individual quantum particles detected at any of the outputs of the interferometer have not been absorbed, any non-trivial effect of the absorber on the distribution of these particles over these paths is a counterfactual effect. Here, we quantify counterfactual effects by evaluating the information about the presence or absence of the absorber obtained from the output statistics, distinguishing between classical and quantum counterfactual effects. We identify the counterfactual gain which quantifies the advantage of quantum counterfactual protocols over classical counterfactual protocols, and show that this counterfactual gain can be separated into two terms: a semi-classical term related to the amplitude blocked by the absorber, and a Kirkwood-Dirac quasiprobability assigning a joint probability to the blocked path and the output port. A negative Kirkwood-Dirac term between a path and an output port indicates that inserting the absorber into that path will have a focussing effect, increasing the probability of particles arriving at that output port, resulting in a significant enhancement of the counterfactual gain. We show that the magnitude of quantum counterfactual effects cannot be explained by a simple removal of the absorbed particles, but originates instead from a well-defined back-action effect caused by the presence of the absorber in one path, on particles in other paths.

Title:

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Higher-order maps without causal order: Applications to quantum information processing, communication, and thermodynam-

ics

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The nature of causality remains one of the key puzzles in science. In quantum theory, the causal structure is not subject to quantum uncertainty and plays rather a background role. One can ask whether the background causal structure can be dropped, for example, by respecting causality only locally. Such scenarios of local validity of quantum theory while relaxing the global definite causal order of operations can be described via the machinery of higher-order operations, i.e. supermaps. An important example of scenarios of this kind is quantum SWITCH, a process realizing a quantum superposition of causal orders of operations. Looking for the possible applications of quantum SWITCH has been the subject of growing interest in the scientific community as it could provide communication and computational resources not realizable via standard quantum theory. Moreover, very recently, the benefits potentially offered by quantum SWITCH for thermodynamic and cryptographic tasks have appeared in the spotlight. My talk aims at highlighting the benefits and applications of higher-order maps to information processing, communication, cryptography, and thermodynamics.

Title:

Author:

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Dicke superradiant enhancement of the heat current in circuit QED

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Collective effects, such as Dicke superradiant emission, can enhance the performance of a quantum device. Here, we study the heat current flowing between a cold and a hot bath through an ensemble of N qubits, which are collectively coupled to the thermal baths. We find a regime where the collective coupling leads to a quadratic scaling of the heat current with N in a finite-size scenario. Conversely, when approaching the thermodynamic limit, we prove that the collective scenario exhibits a parametric enhancement over the non-collective case. We then consider the presence of a third uncontrolled {\it parasitic} bath, interacting locally with each qubit, that models unavoidable couplings to the external environment. Despite having a non-perturbative effect on the steady-state currents, we show that the collective enhancement is robust to such an addition. Finally, we discuss the feasibility of realizing such a Dicke heat valve with superconducting circuits. Our findings indicate that in a minimal realistic experimental setting with two superconducting qubits, the collective advantage offers an enhancement of approximately 10% compared to the non-collective scenario

Title:

Author:

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Improving Quantum Circuit Synthesis with Graph Dominators

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In recent years, quantum computing has emerged as a key technology due to its potential to solve computationally intractable problems.
Many quantum algorithms, such as Shor's and Grover's, require implementing combinatorial logic, including complex arithmetic functions, which can demand significant resources.
Thus, realizing quantum algorithms using the minimum number of qubits and quantum gates is crucial for enhancing the applicability of quantum computers.
It has been demonstrated that any irreversible classical computation can be made reversible and thus synthesizable in a quantum circuit with a certain space overhead.
Quantum circuit synthesis involves translating a classical Boolean function into an equivalent quantum circuit.
This process is as complex as solving the reversible pebble game on the logic network representing the classical function, which is a mathematical graph formalism used to analyze computational problem complexity.
Finding an optimal solution for the reversible pebble game is impractical for large networks, and the solution quality directly impacts the number of qubits and quantum gates needed for the final quantum circuit.
In this work, we introduce a novel strategy to solve the reversible pebble game with a minimal number of pebbles for synthesizing a quantum circuit realizing a given classical combinatorial function specified via its multi-rooted XOR-AND Directed Acyclic Graph.
Our proposal uses the concept of graph-dominators from compiler construction theory to improve on current reversible pebble game solvers used in quantum circuit synthesis.
We benchmark the proposed strategy on a set of combinatorial circuits and report significant savings in quantum resources compared to state-of-the-art heuristics.
We quantify the reduction by counting the total number of qubits required to synthesize the circuit and report figures for the corresponding T-count and T-depth.
The proposed algorithm exposes a tunable tradeoff between the available number of qubits and circuit size, enabling the exploration of alternative solutions.

Title:

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Design of a Quantum Walk Circuit to Solve the Subset-sum Problem

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Search algorithms based on quantum walks have emerged as a promising method for addressing computational problems across various domains, including combinatorial optimization and cryptography. Indeed, quantum walks have been proven to provide a theoretical quadratic speedup in search algorithms compared to the classical paradigm of computation. Additionally, recent literature shows reduced computational complexity relative to the widely-used and generic Grover-based quantum search algorithm when it is used to solve specific problems such as element distinctness, information set decoding, and claw finding.

In this work, we present a complete implementation of a quantum walk search to solve the subset-sum problem. By modeling the domain space as nodes of a Johnson graph, we enhanced the efficiency of the solver with respect to existing theoretical quantum proposals. Our analysis assumes a

fault-tolerant quantum computation regime, setting aside discussions of noise correction and hardware architectures for future research. We derive closed-form complexity metrics in terms of the number of quantum gates, number of qubits, and the depth of the quantum circuit. Unlike state-of-the-art theoretical approaches, our proposal does not rely on an exponentially-sized QRAM, but only requires a polynomial amount of qubits. We also express the complexity metrics of our circuits using the Clifford+T gate set, widely regarded as the most promising for fault-tolerant quantum computation. Our implementation is compared with a Grover-based search approach, demonstrating improvements in both depth and depth-times-number of qubits metrics across a range of problem sizes, from practically solvable subset-sum instances to those large enough for constructing post-quantum cryptosystems.

The proposed design serves as a building block for efficient quantum search algorithms modeled on Johnson graphs, bridging the gap between existing theoretical complexity analyses and providing finite-regime complexity measures.

Title:

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Quantum spatial search with long-range hopping

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Spatial searches by continuous-time quantum walks have been rigorously studied on lattices with nearest-neighbor hopping, in which search capabilities worsen with decreasing lattice dimension when $d \leq 4$. With the addition of long-range hopping, where the hopping rate τ decays as a power-law with the inter-site distance $\tau \sim \ell^{-\alpha}$, we can avert this deterioration in performance. More precisely, we recover $\mathcal{O}(\sqrt{N})$ runtimes for quantum spatial search conducted on low-dimensional cubic lattices of N sites. This is established via an asymptotic analysis of the spectral gap of the lattice's associated discrete Laplacian. The asymptotics also shed light on the interplay between the lattice's Euclidean dimension d and the long-range hopping exponent α, requiring $\alpha < 3d/2$, $d \in [1, 4]$, for high-fidelity searches in $\mathcal{O}(\sqrt{N})$ runtime. Extending the study to also include Euclidean dimensions $d > 4$, we establish that the *spectral dimension* d_s must satisfy the constraint $d_s > 4$ to achieve optimal search. Moreover, the spectral dimension d_s relies on the Laplacian's spectral density and does not uniquely define the underlying lattice structure, thereby providing a promising metric to understand the complexity class of quantum search algorithms on different graph architectures.

Title:

Author:

20

An efficient finite-resource formulation of non-Abelian lattice gauge theories beyond one dimension

Autore: Pierpaolo Fontana[1]

Coautore: Alessio Celi [1]; Marc Miranda Riaza [1]

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We construct an efficient scheme for the quantum and classical simulation of non-Abelian lattice gauge theories beyond one spatial dimension. First, 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. 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. This dualization procedure simplifies the magnetic part of the Hamiltonian, while introducing non-localities in the electric terms. Then, we determine a convenient representation of the Hamiltonian by choosing the local basis for small and big loops variationally, minimizing the truncation error and allowing us to compute the running of the coupling with finite resources for all coupling regimes on small tori. This method enable computations at arbitrary values of the bare coupling and lattice spacing with current quantum computers/simulators and tensor-network calculations, in regimes otherwise inaccessible.

Title:

Author:

21

Optimization of Quantum Channels and its Applications to Quantum Computing

Autore: Giuseppe Clemente[1]

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We introduce a framework for the optimization of parameterized quantum channels induced by both noise in quantum circuits and control noise, exploring a wide range of quantum computing applications. In particular, we discuss the tradeoff between the implementation with either Stinespring, stochastic, or combinations of both representations, in the context of some practical use cases.

Title:

Author:

22

Non-Markovian dynamics and the ground state of many-body systems

Autore: Giuliano Chiriacò[1]

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In this work I discuss the connection between the dissipative dynamics of non-Markovian systems and the ground state of certain related many-body systems.

Title:

Author:

23

Smarter Partitioning of ZX-Diagrams for Classical Simulation of Quantum Circuits

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The task of classically simulating quantum circuits is a particularly useful one, with applications including verifying the behaviour of quantum hardware and simulating quantum many-body problems. However, it is a notoriously difficult task to solve efficiently, as –for a logically complete gateset –the runtime complexity grows exponentially with the scale of the circuit. Recent literature has shown that representing quantum circuits in the graphical language of ZX-diagrams, and applying known decompositions of sets of computationally costly T-gates into sums of computationally cheap states, can allow circuits to be classically simulated in $O(2^{\alpha t})$ time, for some $\alpha < 1$.

In our work, we expand upon this by presenting a method by which a quantum circuit, expressed as a ZX-diagram, may be recursively partitioned into k smaller counterparts which may each be computed independently at an exponentially reduced runtime. By appropriately cross-referencing the resulting scalars of computing these independent parts, one can arrive at a solution equivalent to having classically simulated the original circuit. By heuristically balancing the estimated costs of (a) computing the partitioned segments and (b) cross-referencing their results, we show how the partitioner can be automatically optimised to minimise the number of calculations required.

In benchmarking our method on randomly generated circuits, we show consistent improvements of many orders of magnitude versus the current state of the art ZX-decomposition approaches, particularly for deep circuits of relatively few qubits and shallow circuits of many qubits, as well as other circuits which inherently lend themselves to be efficiently partitioned. There is no upper limit to the improvement it can achieve, and experimentally we found many examples of circuits for which our method could compute in under one second what the best alternative approach would require an estimated years to complete.

Title:

Author:

24

Dissipative stabilization of entangled qubit pairs in quantum arrays

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We study the dissipative stabilization of entangled states in arrays of quantum systems. We show that by engineering a single localized dissipative channel, we can drive the entire array towards stationary entangled states. These states exhibit entanglement between distant, non-directly interacting qubits across the entire array. We further analyze the stability of these generated entangled

states against imperfections and noise. We also explore the possibility of simulating these models on a quantum computer.

Title:

Author:

25

Effects of Coloured Noise Environments to the Coherence Time of Open Quantum Systems

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The use of Stochastic Schrödinger Equations (SSE) to describe open quantum systems is a well-known class of methods, that can be used as an unravelling scheme of associated Quantum Master Equations and as a starting point to derive new ones. From the perspective of simulating quantum systems in Quantum Computers (QC), these methods are of great importance [Lloyd, S. (1996), Science, 273(5278); Hu, Z., Xia, R., Kais, S. (2020), Scientific Reports, 10(1)], as one can exploit stochastic averages to implement intrinsically contractive mappings since each trajectory is a unitary evolution of the system, and harnesses the need for repeated noisy measures in lieu of parallelization. Recent studies have shown the ability to engineer environmental effects, in particular concerning non-Markovian environments [Cialdi, S., Benedetti, C., Tamascelli, D., Olivares, S., Paris, M. G. A., Vacchini, B. (2019), Physical Review A, 100(5); Carmele, A., Parkins, S., Knorr, A. (2020), Physical Review A, 102(3)]. Such noises can be detrimental to or enhance the coherence time and the transport properties of the system [Butler, E. P., Fux, G. E., Ortega-Taberner, C., Lovett, B. W., Keeling, J., Eastham, P. R. (2024), Physical Review Letters, 132(6)]. Here, we present a theoretical description of different coloured noises-driven SSE starting from the model presented in [Barchielli, A., Pellegrini, C., Petruccione, F. (2010), Europhysics Letters, 91(2)], leading to non-Markovian quantum evolution in small model systems, and the associated QME. We show the differences between different interpretations, the differences with respect to the usual memoryless approximations and the effects on initial coherence time and stationary distributions.

Title:

Author:

26

Entangled photonic states from semiconductor quantum dots

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Single-photon sources based on semiconductor quantum dots are optimal solutions in several applications in quantum information processing due to their high single-photon indistinguishability,

on-demand generation, and low multiphoton emission. However, the generation of entangled photons represents a challenging task. A possible solution relies on the interference in probabilistic gates of identical photons emitted at different pulses from the same source. Here, we show the results of entangled state generation by using two different approaches. The first is based on a probabilistic gate that generates entangled photon pairs in the polarization and in the orbital angular momentum degree of freedom. We then characterize the entangled two-photon states by developing a complete model considering relevant experimental parameters, such as the second-order correlation function and photons' indistinguishability.
The second approach investigates the properties of the excitation scheme. The resonant configuration enables the generation of states in superposition in the photon's number basis. We show the results regarding the quality of the generation of such quantum states of light together with a possible protocol for teleportation tailored to such a degree of freedom.

Title:

Entangled photonic states from semiconductor quantum dots

Author:

Taira Giordani, Beatrice Polacchi, Francesco Hoch, Giovanni Rodari, Gonzalo Carvacho, Nicolò Spagnolo and Fabio Sciarrino

27

Toward design and simulation of superconducting transmon qubits for quantum sensing and computing

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Coautore: Matteo Borghesi [1]; Pietro Campana [1]; Rodolfo Carobene [1]; Marco Faverzani [2]; Elena Ferri [1]; Danilo Labranca [1]; Roberto Moretti [1]; Angelo Enrico Lodovico Nucciotti [1]; Luca Origo [3]; Claudio Gatti [1]; Andrea Giachero [4]

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In recent years, significant progress has been made across multiple directions to enhance the properties and performance of superconducting quantum devices, which stand as one of the most promising platforms for quantum computing. This R&D has opened up new opportunities to apply this technology in quantum sensing, particularly for fundamental physics purposes such as the search for weakly electromagnetic coupled dark matter candidates, namely axions and dark photons. Leveraging the high sensitivity to AC fields and Quantum Non-Demolition (QND) measurements, superconducting quantum qubits are promising devices for probing the microwave region in the parameter space of these light dark matter candidates.

This contribution highlights the latest advancements from the National Quantum Science and Technology Institute (NQSTI) Spoke 6 and the National Institute for Nuclear Physics (INFN) in the current state-of-the-art microwave single-photon detection exploiting superconducting quantum technologies. Sample chips were designed, fabricated, and initially measured at the National Institute of Standards and Technology (NIST), followed by comprehensive measurements conducted at the cryogenics laboratory at the University of Milano-Bicocca and the INFN Frascati National Laboratories. These recent measurement campaigns demonstrated a strong agreement between simulations and experimental data, validating all key design parameters and refining our design and simulation workflows.

Currently, our focus is the development and simulation of a two-qubit photon detector which aims to perform coincidence measurements to reduce the dark count rate. A preliminary planar chip layout has been designed exploiting widely-used design software such as Qiskit Metal and KQCircuits while our simulation analysis employs the Lumped Oscillator Model (LOM) and the Energy Participation Ratio (EPR) to extract and optimize Hamiltonian parameters.

These efforts have the potential to significantly enhance superconducting quantum technologies and introduce novel devices and detection schemes to the realm of quantum sensing.

Title:

Toward design and simulation of superconducting transmon qubits for quantum sensing and computing

Author:

Marco Gobbo

28

Quantum-noise-driven Generative Diffusion Models

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Introduction

Generative Diffusion Models (GDMs) are an emerging Machine Learning paradigm where data is corrupted with classical noise and then a Neural Network (NN) learns to remove it in order to recover the unknown initial data distribution. We propose three approaches for a quantum generalization of GDMs with different combinations of classical/quantum forward and backward dynamics as in Fig. 1. Here, quantum noise is exploited as a beneficial ingredient to generate complex distributions.

Methods

We train the Classical-Quantum GDM model using a dataset composed of random points distributed along a line segment. The diffusion process is implemented via a classical Markov chain of Gaussian transition kernels. The denoising process is realized via a parameterized quantum circuit trained to estimate mean and covariance of the kernel of a denoising Markov chain. For the Quantum-Classical (QCGDM) and Quantum-Quantum (QQGDM) models, the quantum forward dynamics is initialized with a pure quantum state that is iteratively degraded by depolarizing channels until it is maximally mixed. In QCGDMs the denoising is implemented with NNs trained to simulate a dynamic to obtain an approximation of the initial state. In QQGDMs the backward is realized with a non-unitary quantum dynamic in the context of open quantum systems.

Results

The results of a simulation of a CQGDM is shown in Fig. 2a. The model reconstructs the initial data distribution with a good approximation quantified by the Kullback-Leibler divergence between the original and reconstructed distributions. In Fig. 2b we show the evolution of the loss during the training of the model. In Fig. 2c and 2d we show the simulation on a single-qubit system for ten QCGDMs and QQGDMs, respectively. In Fig. 2e is reported the evolution of the loss during the training of both models.

Discussion

Quantum systems can represent intractable distributions that are classically inefficient to reproduce. At the best of our knowledge, CQGDM and QCGDM are the first implementations of hybrid classical-quantum diffusion models. This work pave the way for new quantum generative diffusion algorithms for real-world applications, and the design and realization of quantum GDMs could alleviate and reduce the computational resources.

Title:

Author:

29

Quantum switch instabilities with an open control

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The superposition of causal order shows promise in various quantum technologies. However, the fragility of quantum systems arising from environmental interactions, leading to dissipative behavior and irreversibility, demands a deeper understanding of the possible instabilities in the coherent control of causal orders. In this work, we employ a collisional model to investigate the impact of an open control system on the generation of interference between two causal orders. We present the environmental instabilities for the switch of two arbitrary quantum operations and examine the influence of environmental temperature on each potential outcome of control post-selection. Additionally, we explore how environmental instabilities affect protocol performance, including switching between mutually unbiased measurement observables and refrigeration powered by causal order superposition, providing insights into broader implications.

Title:

Author:

30

Quantum phase estimation of molecular excitation energies with compressed sensing

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Quantum phase estimation is a flagship algorithm for quantum simulation on fault-tolerant quantum computers. Recently, the scientific community has begun developing algorithms that maintain similar accuracy scaling but rely on shallower circuits, making them more suitable for early fault-tolerant computers[1]. Building on a recent proposal by Zhang et al.[2], we provide numerical evidence that off-the-grid compressed sensing[3] protocols, combined with state-of-the-art signal classification algorithms[4], enable the simultaneous estimation of multiple eigenvalues of a unitary matrix using the Hadamard test. We apply this protocol to estimate the singlet-triplet gap in a series of polyacene molecules, which are typically used as testbeds for studying strong electronic correlation. We argue that this algorithm may offer a potential quantum advantage by examining the efficacy of

this protocol with respect to the initial state overlap, sampling noise, and the number of queries to the Hadamard circuit. These findings suggest that the integration of these techniques could pave the way for more practical and scalable quantum simulations, potentially accelerating progress in quantum chemistry and materials science.

[1] Katabarwa, A., Gratsea, K., Caesura, A., & Johnson, P. D. (2024). PRX Quantum, 5(2), 020101.

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Title:

Author:

Davide Castaldo

31

Bose and Fermi Polarons in Atom —Ion Hybrid Systems

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Charged quasiparticles dressed by the low excitations of an electron gas constitute one of the fundamental pillars for understanding quantum many-body effects in some materials. Quantum simulation of quasiparticles arising from atom-ion hybrid systems may shed light on solid-state uncharted regimes. Here, we will discuss ionic polarons created as a result of charged dopants interacting with a Bose-Einstein condensate [1,2] and a polarized Fermi gas [3]. Here, we show that even in a comparatively simple setup consisting of charged impurities in a weakly interacting bosonic medium and an ideal Fermi gas with tunable atom-ion scattering length, the competition of length scales gives rise to a highly correlated mesoscopic state in the bosonic case; in contrast, a molecular state appears in the Fermi case. We unravel their vastly different polaronic properties compared to neutral quantum impurities using quantum Monte Carlo simulations. Contrary to the case of neutral impurities, ionic polarons can bind many excitations, forming a nontrivial interplay between few and many-body physics, radically changing the ground-state properties of the polaron.

[1] Astrakharchik, G.E., LAPA, Schmidt, R. et al. Ionic polaron in a Bose-Einstein condensate. Commun Phys 4, 94 (2021).

[2]. Astrakharchik, G.E., LAPA., Jachymski, K. et al. Many-body bound states and induced interactions of charged impurities in a bosonic bath. Nat Commun 14, 1647 (2023).

[3] R.Pessoa, S. A Vitiello, LAPA. Fermi polaron in atom-ion hybrid systems. ArXiv:2401.05324 (2024).

Title:

Author:

32

Stochastic Gaussian non-Markovian equations from the Keldysh contour formalism

Autore: Antonio D'Abbruzzo[None]; Vasco Cavina[None]; Vittorio Giovannetti[None]

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We discuss the derivation of Gaussian non-Markovian quantum stochastic master equations using the technique of the Keldysh contour. First, we derive a general expression for the dynamics of a quantum system in contact with a Gaussian environment. Then, we use it to re-derive the stochastic von Neumann equation: our approach clarifies that the two noises characterizing such equation can be interpreted as a single complex stochastic field defined on the Keldysh contour.
Moreover, we show how such a noise can be reduced to a physical-time one at the price of turning the master equation into a convolution equation, similarly to non-Markovian quantum diffusion equations.
Contrary to existing approaches, our equation is however described by a real noise instead of a complex one. The insight offered by our method is also used to envision a semiclassical scenario in which the noise can be interpreted in terms of a measurement process upon the environment.

Title:

Author:

33

Simulation of Fermionic Circuits of Molecular Systems using a Tensor Network Emulator

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Coautore: Davide Castaldo [1]; Stefano Corni [1]

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Quantum computing is currently in the noisy intermediate-scale quantum (NISQ) era and an ever increasing effort has been put in finding application where "quantum utility" can be found before fault tolerance. In the current landscape Variational Quantum Eigensolver (VQE) is one of the most studied algorithm for applications in quantum chemistry and condensed matter. The VQE algorithm consists in taking a carefully initialized qubit register apply a parametrized quantum circuit to it to model the physics and entanglement of the electronic wavefunction and then measure the Hamiltonian expectation value from the obtained trial wave function. The parameters of the applied quantum circuit are iteratively updated, after each set of measurements, until convergence is reached. The VQE is a promising algorithm since it can theoretically find the ground state of a Hamiltonian in polynomial time and is relatively resilient to quantum hardware noise. In spite of these advantages several questions remain open in order to determine if a real quantum advantage can be reached using this approach. In particular the presence of vanishing gradients and increment of the number of iterations required to optimize the variational parameters with respect to the size of the system simulated are still relatively unexplored aspects that could be decisive in defining the final performance of the VQE.
In this work making use of a highly parallelizable Tensor Network quantum computer emulator we explore the performance of different VQE approaches such as UCCSD, ADAPT-VQE, Tetris-ADAPT-VQE on relatively extended molecules such as H_2O, NH_3, C_2H_4, considering the scaling of both the number of gradients and variational parameters calculated. We then analyze/benchmark the scalability of our emulator and evaluate its possible future use for the development of new quantum algorithm. Making use of the characteristic of our emulator we will also evaluate the entanglement production during variational optimization of large molecular systems.

Title:

Author:

34

Spectroscopic characterization of the Markov to non-Markov transition in qubit-impurity systems

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The behavior of many dissipative systems is generally described by a non-Markovian dynamics. Memory effects associated to non-Markovianity may lead to revival of coherence and entanglement and may be exploited as resources for quantum computation [1–3]. In this work, we study a toy model system of a qubit coupled to an incoherent impurity [3–5] which has been shown to exhibit a transition from a Markovian regime to a non-Markovian dynamics [6, 7], depending on tunable parameters of the system. We investigate this behavior by quantifying the non-Markovianity [8, 9] and by studying the frequency spectrum of the qubit coherence. We study the phase diagram in several regimes and show that the transition is tuned by the qubit-impurity interaction strength and by the temperature of the impurity. Our work aims at introducing spectroscopic witnesses that are easy to measure and are able to quantify the non-Markovianity of a system.

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Title:

Author:

35

Integrated conversion and photodetection of virtual photons in an ultrastrongly coupled superconducting quantum circuit

Autore: Giorgio Anfuso[1]; Luigi Giannelli[2]; Miroslav Grajcar[3]; Gheorghe Sorin Paraoanu[4]; Elisabetta Paladino[2]; Giuseppe Falci[2]

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The ground-state of an artificial atom coupled to quantized modes in the Ultra-Strong Coupling regime is entangled and contains an arbitrary number of virtual photons.
The problem of their detection, raised since the very birth of the field, still awaits experimental demonstration despite the theoretical efforts in the last decade.
In a recent work [1] it has been shown that experimental limitations can be overcome by leveraging an unconventional design of the artificial atom with advanced coherent control techniques.
In this work we study a simple scheme of control-integrated continuous measurement which makes remarkably favourable the tradeoff between measurement efficiency and backaction showing that the unambiguous detection of virtual photons can be achieved within state-of-the art quantum technologies [2].
Work supported by the PNRR MUR project PE0000023-NQSTI

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[2] Luigi Giannelli et al. "Integrated conversion and photodetection of virtual photons in an ultrastrongly coupled superconducting quantum circuit". en. In: The European Physical Journal Special Topics (Sept. 2023). issn: 1951-6355, 1951-6401. doi: 10.1140/epjs/s11734-023-009890. url: https://link.springer.com/10.1140/epjs/s11734-023-00989-0 (visited on 11/17/2023).

Title:

Author:

36

Circuit Quantum Electrodynamics with two-dimensional material-based devices

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Hybrid superconductor-semiconductor systems are platforms where superconducting cavities are coherently coupled to semiconductor devices. Lately, they have become promising platforms for quantum information processing since they have shown compatibility with high magnetic fields and have opened the possibility of realizing noise-protected qubits. In the above framework, devices composed of graphene combined with superconductors, such as the so-called graphene Josephson junction, embedded in nanocircuits have shown exciting potential applications in quantum technologies due to the possibility of tuning resonant frequencies and couplings in situ by exploiting the gate voltage tunability and the peculiar low energy characteristics of 2D materials. In this work, we studied the inductive interaction between a superconducting loop with an embedded short ballistic graphene Josephson junction and a quantum LC resonator. Specifically, within a mean-field approach, we analyzed how the properties of the global system ground state are affected by the light-matter coupling strength. Furthermore, we computed the hybridized light-matter excitations spectrum by calculating the retarded linear response function of the quantum LC resonator flux.

Title:

Author:

37

Spin orbit coupling effects in a graphene Josephson junction

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We study a Graphene Josephson Junction (GJJ) where the inner graphene layer is subjected to a strong Spin-Orbit Coupling (SOC) by proximity effect. This could be achieved, for example, by growing the graphene layer on top of a transition metal dichalcogenide. The SOC terms heavily modify the band structure of the inner graphene layer, inducing different topological phases with associated helical or quasi-helical edge modes. In our work, we focus on the ballistic and short junction limits and, in particular, we study the effects of the SOC interaction on the supercurrent. We follow an analytical approach based on the continuum model for the bulk contribution. We find that there are combinations of spin-orbit couplings that, by opening a gap (topological or not) in the system, drastically suppress the bulk supercurrent. Other combinations, instead, can enhance it, effectively acting as chemical potential. For the edge contribution we made us of a tight-binding procedure based on the Kwant python package. We study the robustness of the edge contribution, given by the helical or quasi-helical modes, against magnetic impurities and disorder along the edges. Because of the different localization properties, the supercurrent carried along the helical zigzag modes was found to be very sensitive to even a single impurity while, remarkably, the supercurrent carried along the armchair ones showed extreme resilience. We also find that, in a junction configuration, there is virtually no difference between intermediate edges terminations and the zigzag one, giving more experimental relevance to the dispersive quasi-helical edge modes, which we found to be also very resilient against disorder along the edges.

Title:

Author:

38

Cooper quartets in interacting hybrid superconducting systems

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Cooper quartets represent correlated matter at the basis of charge-4e superconductivity and offer a platform for studying four-body interactions, of interest for topologically protected quantum computing and strongly correlated matter. Focusing on solid-state systems, we show how to quantum design Cooper quartets in a double-dot system coupled to ordinary superconducting leads through the introduction of an attractive interdot interaction. A fundamentally novel, maximally correlated double-dot ground state, in the form of a superposition of vacuum $|0\rangle$ and four-electron state $|4e\rangle$, emerges as a narrow resonance in a many-body quartet correlator that leads to non-local coherence and novel phenomenology in the dissipationless transport. The systems represents an instance of correlated Andreev matter and the results opens the way to the exploration of interaction effects in hybrid superconducting devices, and the study of novel correlated states of matter with ingredients available in a quantum solid-state lab.

Title:

Author:

39

Model for magnetism in metal-phosphorous-trichalcogenides

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Recent advancements in the study of transition metal-phosphorous-trichalcogenides (MPX3) have revealed unique electronic and magnetic properties, particularly in their single-layer forms. These materials have garnered significant attention due to their potential applications in spintronics and nano-electronics. The state-of-the-art research has largely focused on Density Functional Theory (DFT) calculations to predict the behaviour and properties of MPX3 compounds.
In this project, we aim to develop a theoretical model to understand the behaviour of a single-layer MPX3 sample during an experiment where the resistance was measured with the current flowing perpendicular to the layer. Our goal is to create a model that not only explains the experimental observations but also reproduces the results presented in numerous DFT studies. This model will provide deeper insights into the charge transport mechanisms and help bridge the gap between experimental data and theoretical predictions.

Title:

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Detecting correlations in two qubits by Machine Learning

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We propose a method to detect spatial noise correlations affecting two qubits.
Our sensor consists in two ultra-strongly coupled qubits driven by a
two-tone field. The dynamics is reduced to an effective three-level system in a ladder configuration.
We analyze the parameters regime for which it is possible to effectively apply the
STIRAP protocol transfers population from the ground state of the two-qubits to the
doubly excited state. By analyzing the efficiency under different pulse conditions, it is possible to detect the correlations of noise affecting the two qubits, and to determine its
Markovianity [1].

[1] Noise classification in small quantum networks by Machine Learning, Shreyasi Mukherjee, Dario Penna, Fabio Cirinnà, Mauro Paternostro, Elisabetta Paladino, Giuseppe Falci, Luigi Giannelli. arXiv:2405.01987"

Title:

Author:

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Multimodal jaynes Cummings Model Interacting with a spin bath

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Most open quantum systems are analyzed using master equations to study their dynamics. However, for systems interacting with spin baths, there is no general theory available to derive a master equation belonging to the dynamical semigroup. This requires a case-by-case investigation, posing significant challenges in modeling and understanding these systems. The difficulty arises because the relaxation times between the bath and the system are comparable, making the Markovian approximation ineffective.This work aims to investigate the dynamics of a system interacting with a spin bath where non-Markovian effects are present. Our model consists of two oscillators with different frequencies coupled to a Two-Level System (TLS), which interacts with a spin bath. In this contribution, we propose an exact resolution of a particular system interacting with a spin bath.

Title:

Author:

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Noise classification in small quantum networks by Machine Learning

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We investigate a machine learning based classification of noise acting on a small quantum network with the aim of detecting spatial or multilevel correlations, and the interplay with Markovianity. We control a three-level system by inducing Coherent Tunneling by Adiabatic Passage or Stimulated Raman Adiabatic Passage exploiting different pulse amplitude combinations as inputs to train a feedforward neural network. We show that supervised learning can classify different types of classical diagonal noise affecting the system. Three non-Markovian (quasi-static correlated, anti-correlated

and uncorrelated) and Markovian noises are classified with more than 99% accuracy. On the contrary, correlations of Markovian noise cannot be discriminated with our method. Our approach is robust to statistical measurement errors and retains its effectiveness for physical measurements where only a limited number of samples is available.

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Bose and Fermi Polarons in Atom —Ion Hybrid Systems

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Charged quasiparticles dressed by the low excitations of an electron gas constitute one of the fundamental pillars for understanding quantum many-body effects in some materials. Quantum simulation of quasiparticles arising from atom-ion hybrid systems may shed light on solid-state uncharted regimes. Here, we will discuss ionic polarons created as a result of charged dopants interacting with a Bose-Einstein condensate [1,2] and a polarized Fermi gas [3]. Here, we show that even in a comparatively simple setup consisting of charged impurities in a weakly interacting bosonic medium and an ideal Fermi gas with tunable atom-ion scattering length, the competition of length scales gives rise to a highly correlated mesoscopic state in the bosonic case; in contrast, a molecular state appears in the Fermi case. We unravel their vastly different polaronic properties compared to neutral quantum impurities using quantum Monte Carlo simulations. Contrary to the case of neutral impurities, ionic polarons can bind many excitations, forming a nontrivial interplay between few and many-body physics, radically changing the ground-state properties of the polaron.

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Author: