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ICE-7
Quantum Information in Spain
Granada 23-27 May 2022

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Diamond spin qubits for quantum technologies

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Synthetic diamond has recently emerged as a candidate material for a range of quantum-based applications including: secure quantum communication, quantum information processing and quantum sensing. In such applications, the synthetic diamond acts as a host for impurities or defects, acting like a solid-state atom trap. The quantum states of these impurities, such as the Nitrogen-Vacancy (NV) and Silicon-Vacancy (SiV) defects, can be individually manipulated and made to interact, and photons of light emitted from these impurities can be used to read out. Notably, synthetic diamond (along with silicon carbide) offers advantages over competitive materials as the quantum properties of NV centres it hosts can be manipulated and probed at room temperature. In this presentation we will show how single colour centres can be created with a few nanometres accuracy and coherent dipole-dipole coupling was employed to generate their entanglement. We will discuss further development of the field of quantum information processing and quantum communication. Its success critically depends on the ability to improve positioning accuracy, creation yield and readout of individual NV centres.

Symmetry in non-equilibrium quantum processes

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The talk explores the role of symmetry in quantum transport and in driven systems. Symmetry in molecular systems such as benzene rings, LH2 complexes, carbon nanotubes, and C60 can result in multiple steady state solutions in non-equilibrium transport measurements. [1] However, dynamic or static disorder in open systems will break the symmetry and thus the degeneracy of multiple steady-states, leading to a unique current. To reveal the symmetry hidden under disorder, we demonstrate the slow relaxation of dynamical currents and uncover hidden signatures of multiple steady states. [1,2]

Another type of symmetry is the commutativity of coupling operators, exemplified by non-commutative quantum transport [3]. Further, to study the symmetry in driven systems, we have systematically developed Floquet response theory for open quantum systems driven by a strong but periodic driving field and perturbed by a weak but arbitrary probe field.[4] Dynamical symmetries of the Floquet states lead to spectroscopic signatures including symmetry-protected dark states and Floquet-band selection rules. [4]

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Ideal Projective Measurement Have Infinite Resource Costs and Imply Corrections to Existing Relations

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We show that it is impossible to perform ideal projective measurements on quantum systems using finite resources. We identify three fundamental features of ideal projective measurements and show that when limited by finite resources only one of these features can be salvaged. Our framework is general enough to accommodate any system and measuring device (pointer) models, but for illustration we use an explicit model of an N-particle pointer. For a pointer that perfectly reproduces the statistics of the system, we provide tight analytic expressions for the energy cost of performing the measurement. This cost may be broken down into two parts: first, the cost of preparing the pointer in a suitable state, and second, the cost of a global interaction between the system and pointer in order to correlate them. It turns out that even under the assumption that the interaction can be controlled perfectly, achieving perfect correlation is infinitely expensive. We provide protocols for achieving optimal correlation given finite resources for the most general system and pointer Hamiltonians, phrasing our results as fundamental bounds in terms of the dimensions of these systems. Finally, we show on how our results affect Jarzynski and Crook's relations in the context of the two point measurement scheme.

Continuous Variable quantum complex networks

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Experimental procedures based on optical frequency combs and parametric processes produce quantum states of light involving large numbers of spectro-temporal modes that can be mapped and analyzed in terms of quantum complex networks. The protocols enable the implementation of reconfigurable entanglement structures that can go beyond the regular geometry of cluster states and implement graphs with more complex topology. I will revise the experimental procedure for producing large networks and the challenges in producing and classifying non-Gaussian networks.

Surface acoustic waves as testbed for flying electron qubits

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A surface acoustic wave (SAW) is surprisingly efficient to transport a single electron between distant quantum dots [1,2] while preserving in flight its quantum coherent properties [3,4]. The acousto-electric shuttling technique provides thus a perfect testbed to investigate the feasibility of electron-flying-qubit implementations [5]. Here we present our latest results on SAW-driven single-electron transport in a circuit of coupled quantum rails. Mastering picosecond triggering of the transfer process [6] verified via time-of-flight measurements [7], we are capable of synchronising transport along parallel quantum rails. Sending two electrons simultaneously through the coupling region, we observe distinct Coulomb-dominated repulsion – the central ingredient to realise a controlled phase gate for electron flying qubits [8]. Discussing partitioning data of a single electron in the coupling region [5], we further point out the importance of SAW confinement for coherent in-flight manipulation. To address this critical aspect, we finally demonstrate SAW engineering via chirp synthesis enabling single-electron transport with a solitary electro-acoustic pulse. Our results lay the ground for quantum logic circuits with flying electron qubits surfing on sound.

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Measuring relational information between quantum states, and applications

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The geometrical arrangement of a set of quantum states can be completely characterized using relational information only. This information is encoded in the pairwise state overlaps, as well as in Bargmann invariants of higher degree written as traces of products of density matrices. We describe how to measure Bargmann invariants using suitable generalizations of the SWAP test, which we call cycle tests. This allows for a complete and robust characterization of the projective-unitary invariant properties of any set of pure or mixed states. As applications, we describe basis-independent tests for linear independence, coherence, and imaginarity. We also show how Bargmann invariant measurements can be used to characterize multi-photon indistinguishability, and how they enable measurement of the Kirkwood-Dirac quasi-probability representation. This is joint work with Michał Oszmaniec and Daniel Brod, and has appeared in preprint format [1].

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Full-stack quantum computing systems in the NISQ era: optimization and codesign

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The progress in developing quantum hardware with functional quantum processors integrating tens of noisy qubits, together with the availability of near-term quantum algorithms has led to the release of the first quantum computers. These quantum computing systems already integrate different software and hardware components of the so- called "full-stack", bridging quantum applications to quantum devices. In this talk, we will provide an overview on current full-stack quantum computing systems. We will emphasize the need for tight codesign among adjacent layers as well as vertical cross-layer design to extract the most from noisy intermediate-scale quantum (NISQ) processors which are both error-prone and severely constrained in resources. As an example of codesign, we will focus on the development of hardware-aware and algorithm-driven compilation techniques.

AC- Driven Quantum Dot arrays for Quantum Transfer and Quantum Simulation

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The fabrication and control of long semiconductor quantum dot arrays [1] open the possibility to use these systems for transferring quantum information between distant sites. Interestingly, it also opens the possibility of simulating, in quantum dot arrays, complex Hamiltonians as 1D topological insulators. An example of them is the Su-Schrieffer-Hegger (SSH) model, a chain of dimers, which presents chiral symmetry and bond ordering of nearest-neighbor couplings and displays two topological phases. In a finite chain, the presence of protected edge states, allows to transfer electrons between edges, and therefore their implementation is promising for quantum information transfer. However, it does not account for long range hopping which should occur in real systems and which can destroy the topological properties and the edge states formation [2]. In this talk I will show that, by applying an AC-driving protocol, all hopping amplitudes can be modified at will, imprinting bond-order and effectively producing structures such as dimers chains. Importantly, our protocol allows for the simultaneous suppression of all the undesired long-range hopping processes, enhancement of the necessary ones, and the appearance of new topological phases with increasing number of edge states. I will discuss the dynamics of two interacting electrons in a 12-QD array with different number of edge states. The correlated dynamics, which can be experimentally detected with QDs charge detectors, allows to discriminate between different topological phases and importantly, it opens a new avenue for quantum state transfer protocols [3,4].

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Reservoir computing with qubit networks

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Reservoir computing is a supervised machine learning approach rooted in the framework of neural networks. This unconventional computing method allows for excellent performance in processing temporal series, as in speech recognition and forecasting, with an easy training strategy. Recent developments of reservoir computing and extreme learning machines are moving from classical to quantum implementations, being these also possible in NISQ devices.

The first proposal of quantum reservoir computing was based on a qubit reservoir, in a disordered transverse Ising model, and displayed a promising performance [1], even with few qubits exploiting the Hilbert space dimension of quantum states. In order to achieve this performance, it was then found to be critical the ability of the system to thermalize or localize, being the thermal phase naturally adapted to the requirements of quantum reservoir computing [2].

Still, for continuous temporal series processing, a key issue is how to monitor the output efficiently when including the effect of measurement. Recent results about different strategies that can be devised and their efficiency will be presented.

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Topological light-matter interfaces with large topological invariants

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Topological light-matter interfaces, that are, systems where quantum emitters interact with topologically non-trivial photonic modes is one of the frontiers of topological photonics. The interplay between topology and strong interactions from the non-linear emitter level structure can lead to qualitatively different quantum optical phenomena, and open new avenues for engineering robust quantum gates between emitters or photons that can be harnessed for different quantum technologies. These exciting perspectives have led to the first implementations based on coupling quantum dots to topological photonic crystals or superconducting qubits to coupled microwave resonators, among others.

In this presentation, we will discuss about the physics emerging when the topological photonic systems display large winding phases in 1D, or large Chern numbers in 2D topological insulators. In particular, we will show how in the 1D scenario the topological phases lead to qualitatively different shapes for the emitter-emitter interactions induced in topological band-gaps, among other effects. In the 2D systems, we will characterize the emergence of a topological multi-mode waveguide in their edges, and show how it can lead to time-bin-like entangled emission patterns or exotic collective decays.

Coupling 3-Josephson junctions flux qubits for Adiabatic Quantum Computation

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Many platforms have been proposed to implement Adiabatic Quantum Computation, from superconducting circuits to trap ions. Nevertheless, it is still not clear how to obtain general and fully tunable multi-qubits dynamics in any of those platforms. General enough qubit-qubit interactions would allow, for instance, to reproduce the dynamics of non-stoquastic Hamiltonians, the ones for which classical Monte-Carlo methods fail, opening the way to Universal Adiabatic Quantum Computation.

In this talk, we analyse the coupling between two 3-Josephson junctions flux qubits and

present the effective Hamiltonian that controls the dynamics of the system when the two qubits are coupled via a capacitor and/or via a Josephson junction [1]. We show that those two elements allow engineering a fairly large family of qubit Hamiltonians with XX, YY and ZZ, including fully non-stoquastic interactions and ultrastrong coupled ones. In addition, we discuss the capacitive coupling between a flux qubit and an LC-resonator [2] and show ultrastrong coupling in a direction perpendicular to that of the commonly studied inductive coupling, leaving the door open to the simulations of quantum optics models unexplored up to date.

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Quantum verification with few copies

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As quantum technologies advance, the ability to generate increasingly large quantum states has experienced rapid development. In this context, the verification of large entangled systems represents one of the main challenges in the employment of such systems for reliable quantum information processing. Though the most complete technique is undoubtedly full tomography, the inherent exponential increase of experimental and post-processing resources with system size makes this approach unfeasible even at moderate scales. For this reason, there is currently an urgent need to develop novel methods that surpass these limitations. In this talk, I will present novel techniques focusing on a fixed number of resources (sampling complexity), and thus prove suitable for systems of arbitrary dimension. Specifically, a probabilistic framework requiring at best only a single copy for entanglement detection will be reviewed, together with the concept of shadow and selective quantum state tomography, which enables the estimation of arbitrary elements of an unknown state with a number of copies that is independent of the system's size. These hyper-efficient techniques define a dimensional demarcation for partial tomography and open a path for novel applications.

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A 7-Tesla Penning-Trap System for Precision Quantum Measurements

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At the University of Granada (UGR Ion Trapping group) [1], we have built a 7-tesla Penning-trap platform aiming at high-precision laser-based measurements [2]. The possibility of manipulating ions and molecules of any mass-to-charge ratio or the improved stability compared to Paul traps make this Penning trap a unique facility. $^{40}Ca^{+}$ is used as a sensor ion that can be laser-addressed to cool the so-called unbalanced crystal and to perform readout operations in motional metrology or quantum logic spectroscopy [3,4].

In this contribution, we will present the status of the TRAPSENSOR experiment and describe the latest results. Doppler cooling of single ions and two-ion crystals has been studied in detail, particularly concerning the axialization technique [5]. In parallel, we have developed a new laser-ablation universal ion source, where we have produced target ions such as thorium or rhenium. These species must be injected in the Penning trap together with $^{40}Ca^{+}$ for cooling and to perform the measurements envisaged. In this respect, we will address ground-state cooling of the single ion or ion pair foreseen by means of our new high-finesse cavity setup coupled to a Ti:Sa laser. We will also comment on a new approach based on quartz resonators coupled to trapped ions [6].

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Bell nonlocality is not sufficient for the security of standard device-independent quantum key distribution protocols

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Device-independent quantum key distribution is a secure quantum cryptographic paradigm that allows two honest users to establish a secret key, while putting minimal trust in their devices. Most of the existing protocols have the following structure: first, a bipartite nonlocal quantum state is distributed between the honest users, who perform local measurements to establish nonlocal correlations. Then, they announce the implemented measurements and extract a secure key by post-processing their measurement outcomes. We show that no protocol of this form allows for establishing a secret key when implemented on any correlation that can be obtained by measuring local projective measurements on certain entangled nonlocal states, namely on a range of entangled two-qubit Werner states. To prove this result, we introduce a technique for upper-bounding the asymptotic key rate of device-independent quantum key distribution protocols, based on a simple eavesdropping attack. Our results imply that either different reconciliation techniques are needed for device-independent quantum key distribution in the large-noise regime, or that Bell nonlocality is not sufficient for this task.

This submission is based on Phys. Rev. Lett. 127, 050503 (2021)

Topological Traveling-Wave Parametric Amplification

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Amplification is at the heart of many different technologies. Achieving large gain and low noise during the amplification process is one of the main objectives during their development. Here we will show that the ideas from topological condensed matter systems can be used to design directional high-quality amplifiers where topology plays a crucial role: the robustness of amplification to disorder is linked to a topological invariant, phase-matching between modes is automatically implemented, the gain is exponential with the number of sites in the system and its signal-to-noise ratio is quantum limited.

I will discuss the theory behind topological amplification and one possible experimental implementation in the microwave regime using Josephson junctions.

Fundamental limits in Bayesian thermometry and attainability via adaptive strategies

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We investigate the limits of thermometry using quantum probes at thermal equilibrium within the Bayesian approach. We consider the possibility of engineering interactions between the probes in order to enhance their sensitivity, as well as feedback during the measurement process, i.e., adaptive protocols. On the one hand, we obtain an ultimate bound on thermometry precision in the Bayesian setting, valid for arbitrary interactions and measurement schemes, which lower bounds the error with a quadratic (Heisenberg-like) scaling with the number of probes. We develop a simple adaptive strategy that can saturate this limit. On the other hand, we derive a no-go theorem for non-adaptive protocols that does not allow for better than linear (shot-noise-like) scaling even if one has unlimited control over the probes, namely access to arbitrary many-body interactions.

Entanglement catalysis for quantum states and noisy channels

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Many applications of the emerging quantum technologies, such as quantum teleportation and quantum key distribution, require singlets, maximally entangled states of two quantum bits. It is thus of utmost importance to develop optimal procedures for establishing singlets between remote parties. As has been shown very recently, singlets can be obtained from other quantum states by using a quantum catalyst, an entangled quantum system which is not changed in the procedure. In this work we put this idea further, investigating properties of entanglement catalysis and its role for quantum communication. For transformations between bipartite pure states we prove the existence of a universal catalyst, which can enable all possible transformations in this setup. We demonstrate the advantage of catalysis in asymptotic settings, going beyond the typical assumption of independent and identically distributed systems. We further develop methods to estimate the number of singlets which can be established via a noisy quantum channel when assisted by entangled catalysts. For various types of quantum channels our results lead to optimal protocols, allowing to establish the maximal number of singlets with a single use of the channel.

Dynamical decoupling techniques and complex systems

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Quantum Sensing with nitrogen-vacancy (NV) centers in diamond promises to revolutionize detection and imaging techniques. Via the adequate application of suited radiation patterns over NVs, one can increase spectral resolution up to a level that enables the detection of complex systems in different scenarios, such as those involving large static magnetic fields. In this talk I will explain distinct quantum control protocols based on dynamical decoupling techniques, and their combination with data processing methods for techno- logical applications such as imaging at the nanoscale, the interpretation of non-harmonic responses, or the detection of electron spin labels in biomolecules.

Mapping quantum algorithms into molecular spin qudits

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In spite of the progress that qubit-based computers have made in the implementation of all kinds of algorithms, the leap to architectures based on d-dimensional building blocks, or qudits, may be crucial to overcome current limitations in both scalability and information storage capacity.

We study how to optimally exploit magnetic molecules, as natural qudits, to implement “à la carte” quantum algorithms. Molecules with large electronic and/or nuclear spins provide a natural platform with multiple operational levels [1, 2]. Operations are driven by electromagnetic pulses resonant with the allowed transitions, which can be realized with EPR techniques or by coupling them to superconducting circuits [3].

Here, we show a theoretical tool that allows translating any quantum algorithm into any given molecular spin qudit, and illustrate its potential with examples for existing molecular systems and diverse algorithms.

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A coherence-theoretic analysis of quantum neural networks

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We investigate the properties of attractor quantum neural networks (aQNNs) using the tools provided by the resource theory of coherence, thus relating quantum machine learning techniques with coherence theory. We show that when the aQNN is characterized by a quantum channel with maximal number of stationary states, then such channel is a non-coherence-generating operation, and that the depth of the neural network is related to its decohering power. Further, we examine the case of faulty aQNNs, described by noisy quantum channels, and derive their physical implementation. Finally, we show that the performance of this class of aQNNs cannot be enhanced either by using entanglement or coherence as external resources.

Fundamental limits for quantum communication: designing degradable extensions

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We develop methods to construct degradable extensions of quantum channels. A central role in our construction is played by flagged extensions of quantum channels. With these constructions we obtain state-of-the-art upper bounds on quantum and private capacities of physically motivated noise models, in both discrete and continuous variables, e.g.: depolarizing channel, BB84, generalized amplitude damping, thermal attenuator and amplifier, and additive Gaussian noise.

Our bounds are based on the following results:

-We derive sufficient conditions for degradability of flagged extensions and establish explicit upper bounds for Pauli channels;

-By generalizing the construction for discrete variable channels, we establish a degradable Gaussian flagged extension of the additive Gaussian noise channel; we also find a new Gaussian degradable extension of the thermal attenuator channel.

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[https://doi.org/10.1103/PhysRevLett.127.210501]

Strong laser field physics and its potential for quantum technology applications

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Strong laser field physics and quantum optics are two research directions founded on the classical and quantum description of the electromagnetic field, respectively [1,2]. While the latter has proven to be a very important field towards the development of quantum technologies [3], the former has been a widely active research direction for studies ranging from relativistic electron acceleration to ultrafast electronics [4,5]. However, the direction of both research domains has remained uncoupled over the years, primarily due to the highly successful treatment of the classical electromagnetic field in strong laser field physics. In our recent works, we have looked at the interplay between quantum optics and strong laser field physics by considering the quantum nature of the field [6,7]. These studies show the power of strong laser field dynamics to generate coherent state superpositions, and entangled coherent states with photon numbers and energies orders of magnitude higher than those provided by the current technology [8,9]. Thus, these works set up a basis for a road toward a novel platform of strong field physics for quantum technology.

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Photon-mediated interactions between spin 1 atoms

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Quantum simulators are highly controllable devices that exploit quantum effects to answer questions about another system. They can be built using different platforms, such as ultracold atoms in optical lattices, superconducting circuits or atoms interacting with nanophotonic structures [1]. This last system is particularly interesting because the nanophotonic environment can be tailored to generate exotic photon-mediated interactions between atoms [2], with both dissipative and coherent evolutions, opening the door for the exploration of a wide range of physical models. However, these atoms have been typically considered as two-level systems, which limits the type of models that can be explored [3,4]. Our work considers the full hyperfine structure of the atoms to go beyond this and study effective spin-1 interactions between the quantum emitters, where Raman-assisted transitions allow a mapping to well-known models such as the Ising or the XX spin-1 interactions. These results could be interesting both in quantum simulation (where they could be applied to study spin chains or even simulating some lattice gauge theories [5,6]) and quantum computation (as a way to obtain quantum gates between qutrits [7]).

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1D Abelian gauge theories with MPS

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I will discuss the discovery of a new exotic phase transition in the Abelian Higgs model in 1D seen through the lenses of entanglement as described in https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.128.090601

Exponential decay of mutual information for Gibbs states of local Hamiltonians

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The thermal equilibrium properties of physical systems can be described using Gibbs states. It is therefore of great interest to know when such states allow for an easy description. In particular, this is the case if correlations between distant regions are small. In this work, we consider 1D quantum spin systems with local, finite-range, translation-invariant interactions at any temperature. In this setting, we show that Gibbs states satisfy uniform exponential decay of correlations and, moreover, the mutual information between two regions decays exponentially with their distance, irrespective of the temperature. In order to prove the latter, we show that exponential decay of correlations of the infinite-chain thermal states, exponential uniform clustering and exponential decay of the mutual information are equivalent for 1D quantum spin systems with local, finite-range interactions at any temperature. In particular, Araki's seminal results yields that the three conditions hold in the translation-invariant case. The methods we use are based on the Belavkin-Staszewski relative entropy and on techniques developed by Araki. Moreover, we find that the Gibbs states of the systems we consider are superexponentially close to saturating the data-processing inequality for the Belavkin-Staszewski relative entropy. This is joint work with Andreas Bluhm and Antonio Pérez-Hernández.

Quantum-enhanced sensing experiments with $^{40}Ca^{+}$ ions in a linear Paul trap

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At the Ion Trapping Group at the University of Granada [1], we are developing a novel technique for precision experiments with Penning traps based on the detection of fluorescence photons from a single $^{40}Ca^{+}$ ion. This choice of sensor ion allows us to devise quantum-metrology based schemes in order to perform accurate frequency measurements of the normal modes of an unbalanced crystal formed by the $^{40}Ca^{+}$ sensor ion and the target ion and cooled down to the motional ground state [2].

In this regard, we have built a linear Paul trap apparatus as a test bench setup to assess the achievable sensitivity and precision of the proposed measurement scheme. The entire protocol relies on the coherent manipulation of the internal electronic states of $^{40}Ca^{+}$ in the quantum regime to generate displaced motional Fock states, where the displacement is implemented by an electric field oscillating at the frequency of the target mode [3,4]. These characterization experiments will pave the way towards the realization of motional quantum metrology experiments in the Penning trap setup of the TRAPSENSOR facility [5], where Doppler cooling and crystallization of externally produced $^{40}Ca^{+}$ ions have been recently achieved [6].

In this contribution, we will present the status of the linear Paul trap experiment and the recent results. Sideband spectroscopy on the “clock” transition of a single 40Ca+ ion has been recently achieved, which enables us to determine the average number of phonons of the motional state after Doppler cooling. The on-going work is devoted to performing sideband cooling in order to prepare the ion to the motional ground state of the confining potential, which is a pre-requisite to generate motional Fock states. Finally, we will underline the perspectives for the generation and control of the motional state of $^{40}Ca^{+}$ in the quantum regime in the presence of electric fields for the envisaged quantum-metrology experiments. Manipulation and control in the quantum regime will enable us to position the linear trap setup as a suitable experimental platform to the community working in Quantum Technologies in Spain.

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Towards the development of perceptron-based quantum neural networks

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Unitary perceptrons constitute a elementary base for the physical realization of trainable quantum neural networks. Here, we analyze the experimental implementation of two different approaches and benchmark the networks performance considering several examples. Finally we study the role of quantum resources such entanglement and inspect the agenda of quantum machine learning.

Optimal quantum control of coupling-tunable transmon qubits

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In this talk we analyze the implementation of a fast nonadiabatic CZ-gate through the resonance between the |11> and |20> states of transmon qubits with tunable coupling. We explicitly derive an effective Hamiltonian for the low-energy eigenstates. This allows us to identify different sources of error and design controls based on the theory of dynamical invariants, which have been proven to be particularly attractive due to their reduced leakage and robustness against decoherence. Our results show that these protocols achieve gate fidelities higher than the fast quasiadiabatic dynamics within times that approach the theoretical limit. This study paves the way for large-scale implementation of high-fidelity quantum operations.

Thermodynamics of precision in quantum non-equilibrium steady states

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Many state-of-the-art experiments have established nowadays that genuine quantum features, in particular coherent superposition and entanglement, are among the key ingredients to achieve a “quantum edge” over any classical counterpart. To date, however, analyses have mainly focused on average measured quantities, such as power output or computational time, while neglecting fluctuations, which drive universal phenomena such as phase transitions and which become extremely relevant at the nano-scale. Indeed, managing them is vital to ensure any such device is truly functional. Having a more powerful but less precise machine, i.e. one with large fluctuations, would lead to errors in the case of computation or spluttering in terms of engine power. On top of this, understanding and quantifying the balance between achieving a certain output with a given desired precision and the unavoidable energetic/thermodynamic cost of achieving it is of paramount importance. Thermodynamics of precision is a newborn interdisciplinary research field whose goal is to tackle this problem. The main cornerstone result in this field is known as Thermodynamic Uncertainty Relations (TURs), which expresses in a quantitative way the tradeoff between the signal-to-noise ratio of any steady-state observable and the amount of irreversible entropy production. Originally formulated for classical Markov chains, TURs have been extended and generalized to cover a wide class of classical stochastic phenomena.

Here we will provide the first derivation of a fundamental TUR-like trade-off between current fluctuations and entropy production for quantum systems operating non-equilibrium steady states (NESS). To achieve this goal, we exploit the concept of McLennan/Zubarev non-equilibrium statistical operators and illustrate how the entropy production can be expressed as a quantum relative entropy. Furthermore, by purely relying on the geometry of the manifold of NESS states, we use parameter estimation theory and quantum information concepts in order to bound the co-variance of the currents in the NESS by the entropy production. Since our proof is purely geometrical, this fundamental result generalizes the thermodynamics of precision and the thermodynamic uncertainly beyond the classical Markovian paradigm.

Revealing the Einstein-Podolsky-Rosen paradox with tools from metrology

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The sensitivity of quantum states under small perturbations is the quantity of central interest in quantum metrology. Besides identifying strategies that lead to quantum-enhanced measurement precision, the metrological sensitivity provides detailed information about the state's quantum correlations. In this talk, we use a metrological complementarity relation to formulate the Einstein-Podolsky-Rosen (EPR) paradox and to build a witness for EPR steering [1], a strong form of entanglement. Reid's criterion [2], the most widely used method for steering detection in experimental systems, is based on the uncertainty relation and can be recovered as an approximation to our approach. Focusing on metrological sensitivity enables us to uncover the steering of non-Gaussian states that cannot be revealed by measuring Gaussian properties, such as variances.

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Asymptotic survival of genuine multipartite entanglement in noisy quantum networks depends on the topology

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The study of entanglement in multipartite quantum states plays a major role in quantum information theory and genuine multipartite entanglement signals one of its strongest forms for applications. However, its characterization for general (mixed) states is a highly nontrivial problem and its experimental preparation faces the formidable challenge of controlling quantum states with many constituents. In this work we introduce a subclass of multipartite states, which we term pair-entangled network (PEN) states, as those that can be created by distributing exclusively bipartite entanglement in a connected network, and we study how their entanglement properties are affected by noise and the geometry of the graph that provides the connection pattern. Our motivation is twofold. First, this class represents arguably the most feasible way to prepare genuine multipartite entangled states in practice. Second, the class of PEN states provides an operationally motivated subset of multipartite states in which the well-developed theory of bipartite entanglement can be exploited to analyze entanglement in the multipartite scenario. We show that genuine multipartite entanglement in a PEN state depends both on the level of noise and the network topology and, in sharp contrast to the case of pure states, it is not guaranteed by the mere distribution of mixed bipartite entangled states. Our main result, however, is a much more drastic feature of this phenomenon: the amount of connectivity in the network determines whether genuine multipartite entanglement is robust to noise for any system size or whether it is completely washed out under the slightest form of noise for a sufficiently large number of parties. This latter case implies fundamental limitations for the application of certain networks in realistic scenarios, where the presence of some form of noise is unavoidable. In addition to this, to illustrate the applicability of PEN states to study the complex phenomenology behind multipartite entanglement, we use them to prove superactivation of genuine multipartite nonlocality for any number of parties.

Digital-Analog Quantum Computation and Simulation

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Digital-analog quantum computation is an alternative universal quantum computing paradigm which makes use of the natural (analog) interaction Hamiltonian between qubits as an entangling resource combined with fast single-qubit rotations (digital steps). It is a near-term solution to the limitations of NISQ devices which has shown higher resilience against error noises and better scalability perspectives. Therefore, it is possible to adapt and engineer new quantum algorithms which avoid the noise associated to the two-qubit gates in the digital paradigm. Here, we will introduce the digital-analog paradigm and show its universality in Hamiltonian simulations. Additionally, we will see how quantum algorithms can be adapted to this paradigm, in particular, the quantum Fourier transform and the Harrow-Hassidim-Lloyd. Finally, we will analyze its behavior under sensible noise sources by comparing its performance and scalability against the fully digital one.

Achieving strong spin-photon coupling with a semiconductor hole qubit

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Confined spins in semiconductor structures have recently proven to be a promising quantum technology for scalable quantum computation. Latest milestones in both electron- and hole-based qubits are the demonstrations of high-fidelity operation of a 6-qubit and a 4-qubit processor, respectively [1,2]. These processors rely on the exchange interactions between neighboring qubits, which can be extremely fast and electrically tunable, allowing high-fidelity two-qubit gates. The exchange interaction, however, is local and, hence, limited to nearest-neighbor interactions. One of the most promising technologies for achieving long-range multi-qubit operation is through the use of superconducting cavities as links between distant qubits. Recently, the strong spin-photon coupling has been achieved with electron spins [3-5]. Due to the weak spin-orbit coupling of electrons, the demonstrated couplings, in the order of 10 MHz, are still far from what is needed to perform high-fidelity gates.

In this work, I will cover our recent theoretical and experimental results on spin-photon coupling with hole spins in Silicon. Unlike electrons, holes couple naturally to electrical degrees of freedom due to their large spin-orbit coupling. As I will show, this extremely large electrical susceptibility theoretically allows to couple hole spins to superconducting cavities both in the single- [6] and double-dot [7] regimes. We provide the first experimental demonstration of such coupling [8], exceeding the electron spin-photon couplings by one order of magnitude, bordering the ultrastrong coupling regime.

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Periodically refreshed quantum thermal machines

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We introduce a unique class of cyclic quantum thermal machines (QTMs) which can maximize their performance at the finite value of cycle duration where they are most irreversible. These QTMs are based on single-stroke thermodynamic cycles realized by the non-equilibrium steady state (NESS) of the so-called Periodically Refreshed Baths (PReB) process. We find that such QTMs can interpolate between standard collisional QTMs, which consider repeated interactions with single-site environments, and autonomous QTMs operated by simultaneous coupling to multiple macroscopic baths. We discuss the physical realization of such processes and show that their implementation requires a finite number of copies of the baths. Interestingly, maximizing performance by operating in the most irreversible point as a function of cycle duration comes at the cost of increasing the complexity of realizing such a regime, the latter quantified by the increase in the number of copies of baths required. We demonstrate this physics considering a simple example. We also introduce an elegant description of the PReB process for Gaussian systems in terms of a discrete-time Lyapunov equation. Further, our analysis also reveals interesting connections with Zeno and anti-Zeno effects.

Complete device QND measurement tomography and applications to IBM-Q

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Quantum non-demolition (QND) measurements are a fundamental element for quantum computing. However, they are currently a limiting factor in the performance of quantum devices based on superconducting circuits. In order to improve QND detectors, we require efficient characterization technics to identify and mitigate the source of errors. In this work, we present an efficient scaling strategy to characterize all the measurements of a device by quantum tomography. The protocol reconstructs the Choi matrices that describe the measurements of every single qubit and all the pairs of physically connected qubits. The protocol requires a bounded number of circuits for any number of qubits thanks to an efficient parallelization of the tomography. This allows us to avoid the exponential scaling of a standard QND measurement tomography. Besides, postprocessing can be also solved efficiently by parallelizing it on a classical processor. We perform an experimental implementation of the protocol to fully characterize all the detectors of a 7-qubits IBM-Q quantum device. We use the tomographic estimates to study properties of the measurement such as readout fidelity, qndness, destructiveness, and crosstalk. After that, we apply the method to characterize a custom detector composed by a standard measurement, a reset, and a conditional state preparation.

Inferring non-linear Bell's inequalities tailored to arbitrary spin-*j* ensembles

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Violating Bell's inequalities allows one to certify the preparation of entangled states from minimal assumptions -- in a device-independent manner. Finding Bell's inequalities tailored to many-body correlations as prepared in present-day quantum simulators is however a highly challenging endeavour. Here, we develop a novel data-driven approach valid for arbitrarily-many measurement settings and outcomes, to find Bell's inequalities violated by very coarse-grain features of the system: two-body correlations averaged over all permutations of the subsystems. Our approach offers two main improvements over the existing literature: (1) it is directly designed for any number of outcomes and settings; (2) the obtained BIs are quadratic in the data, offering a fundamental scaling advantage for the precision required in experiments. This very flexible method, whose complexity does not scale with the system size, allows us to systematically improve over the previously known Bell's inequalities robustly violated by ensembles of quantum spins $j = 1/2$; and to discover novel families of Bell's inequalities, tailored to spin-squeezed states and many-body spin singlets of arbitrary spins ($j > 1/2$).

PRX Quantum 2, 030329 (2021)

Macroscopically nonlocal quantum correlations

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It is usually believed that coarse-graining of quantum correlations leads to classical correlations in the macroscopic limit. Such a principle, known as macroscopic locality, has been proved for correlations arising from independent and identically distributed (IID) entangled pairs. In this letter we consider the generic (non-IID) scenario. We find that the Hilbert space structure of quantum theory can be preserved in the macroscopic limit. This leads directly to a Bell violation for coarse-grained collective measurements, thus breaking the principle of macroscopic locality.

The Third Level: NV-centers, Andreev Spin Qubits and Trapped Ions

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In this talk I will present three recent experiments on quantum systems where the involvement of a third level in its control protocol has been crucial to open a new avenue for exploitation in computation, sensing or communication.

First, NV-centers in nanodiamonds, which can be used as highly accurate nanoscale sensors, fail to respond to microwave control pulses at low local magnetic fields. With the design of an effective Raman coupling (ERC) [1], it is possible to circumvent this limitation. The ERC can be achieved by adjustment of the microwave frequency to that of the zero-field line and judicious timing of the pulses, such that the full potential of the spin-1 ground state is put to work. The technique has been recently implemented experimentally [2], paving the way for low-field detection of biomolecules.

Second, Josephson weak links are known to host Andreev quasiparticles. Their high localization and built-in protection against charge noise makes their spin extremely appealing as registers for quantum information. Nevertheless, their implementation was not possible due to the lack of direct control of the spin state. Thorough analysis of the level structure and the implementation of techniques stemming from quantum optics made it clear that the use of high-lying Andreev modes could be used as intermediaries for the coherent control of spin [3]. The final demonstration of such approaches came recently [4] and constitutes groundbreaking progress towards scalable solid-state quantum computers.

Finally, trapped ions have long established themselves as accurate and reliable platforms for quantum information processing. Their operation relies on laser cooling preparation steps, which can be substantially improved by using electromagnetically-induced transparency [5]. These techniques are flexible and can be designed for complex level structures, as recently shown in quantum-clock experiments [6]. Quantum mass spectrometry experiments will also benefit strongly from their implementation [7].

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Constructive neural network models for studying Bell-nonlocality and entanglement

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The advent of deep neural networks has led to numerous applications in the scientific domains. Here, we study their use in studying Bell-nonlocality and entanglement. In particular, we use neural networks to explicitly represent local hidden variable models or separable quantum states. Thus, by training the neural network, it can learn the closest local model/separable decomposition to a fixed target distribution/state. This allows us to infer nonlocality or entanglement properties even in scenarios where conventional methods fail us, such as in networks.

These numeric works have led to a number of interesting insights in Bell nonlocality on networks with independent sources. For example, the neural network conjectured nonlocality for a distribution, and assisted in developing the first optical realization of an experimental proposal in the triangle network (work done in collaboration with ICFO).

I will present these results, with a more generic outlook on how neural networks can be used in quantum foundations.

Finite-time Landauer principle at strong coupling

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Landauer's principle gives a fundamental limit to the thermodynamic cost of erasing information. Its saturation requires a reversible isothermal process, and hence infinite time. We develop a finite-time version of Landauer’s principle for a quantum dot strongly coupled to a fermionic bath. By solving the exact non-equilibrium dynamics, we optimize erasure processes (taking both the dot’s energy and system-bath coupling as control parameters) in the slow driving regime through a geometric approach to thermodynamics. We find analytic expressions for the thermodynamic metric and geodesic equations, which can be solved numerically. Their solution yields optimal finite-time processes that allows us to characterise a fundamental finite-time correction to Landauer's bound, fully taking into account non-markovian and strong coupling effects.

Quantum electronic voting without election authority

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Electronic voting is a very useful but challenging internet-based protocol that despite many theoretical approaches and various implementations with different degrees of success, remains a contentious topic due to issues in reliability and security.

Here we present a quantum protocol that exploits an untrusted source of multipartite entanglement to carry out an election without relying on election authorities, simultaneous broadcasting or computational assumptions, and whose result is publicly verifiable. The level of security depends directly on the fidelity of the shared multipartite entangled quantum state, and the protocol can be readily implemented for a few voters with state-of-the-art photonic technology.

Sequential Test on an Optomechanical Systems under Homodyne detection

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Quantum sensing deals with the with designing quantum devices capable to outperform classical systems.

One of the most promising platform for the near future quantum sensors are continuously monitored quantum systems, where a continuous stream of informations is extracted from the device. However all the strategies used to analyze these data are performed only after a full sequence of measurements has been recorded and no online strategies is applied.

In this talk we present a sequential test, that can be in principle used to run on-line to discriminate between the dynamical parameters of an optomechanical system under homodyne detection.

High-Fidelity Nanoscale NMR Spectroscopy at Large Fields

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Nitrogen-Vacancy centers can perform spectroscopy with unprecedent spatial resolution and low quantity sample requirements. However, the regime of high magnetic fields remains unexplored, as coupling the NV with high-frequency signals is challenging. In this work, we circumvent this problem by mapping the relevant shifts to the amplitude of a driven nuclear signal that can be easily coupled to the NV sensor. Our method allows performing high-resolution nanoscale NMR spectroscopy at high and ultra-high magnetic fields, paving the way to promising applications of quantum sensors.

QAOA pseudo-Boltzmann states

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In this talk we present the main results of arXiv:2201.03358. We provide analytical and numerical evidence that the single-layer Quantum Approximate Optimization Algorithm (QAOA) on universal Ising spin models produces thermal-like states with Gaussian perturbations. We find that these pseudo-Boltzmann states cannot be efficiently simulated on classical computers according to state-of-art techniques, and we relate this distribution to the optimization potential of QAOA. Moreover, we observe that the temperature depends on a hidden universal correlation between the energy of a state and the covariance of other energy levels and the Hamming distances of the state to those energies.

Quantum-inspired solutions to machine learning privacy leaks

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Vast amounts of data are routinely processed in machine learning pipelines, every time covering more aspects of our interactions with the world. When the models processing the data are made public, is the safety of the data used for training it guaranteed? This is a question of utmost importance when processing sensitive data such as medical records, but also for businesses whose competitive advantage lies in data quality. Within machine learning, the focus has been put in protecting models against revealing the presence or absence of any particular datapoint during the training process. The state-of-the-art techniques developed, despite being deployed in commercial systems, consist in adding noise at some stage during the training process, and thus imply a tradeoff between privacy protection and performance.

In this talk, I will argue and practically illustrate that insights in quantum information, concretely coming from the tensor network representations of quantum many-body states, can help in devising better privacy-preserving machine learning algorithms. In the first part, I will show that standard neural networks are vulnerable to a type of privacy leak that involves global properties of the data used for training, thus being a priori resistant to the standard protection mechanisms. In the second, I will show that tensor networks, when used as machine learning architectures, are invulnerable to this leak. Tensor network architectures for machine learning are recently showing to compete and even surpass traditional machine learning architectures in certain cases, and the proof of the resilience is based in the existence of canonical forms for such architectures. Given the growing expertise in training tensor networks and the recent interest in tensor-based reformulations of popular machine learning architectures, these results imply that one may not have to be forced to make a choice between accuracy in prediction and ensuring the privacy of the information processed when using machine learning on sensitive data.

State retrieval beyond Bayes’ retrodiction and reverse processes

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Reversible operations of a physical system are bijective mapping between input and outputs. They are called reversible for a well-defined notion of reverse operation exists: it consists in the inversion of the direction of the element-wise mapping from the space of the outputs to the space of inputs. In quantum mechanics reversible operations are given by unitary operations, while for classical stochastic processes these are permutations. Whenever the bijectivity between the space of inputs and outputs is lost, the standard definition of reverse operation does no longer apply and one is forced defining a notion of generalised reversion. In general, associating to a physical process its intuitive reverse can result to be a quite ambiguous task. It is a standard choice to define the reverse process using Bayes’ theorem, but, in general, this choice is not optimal. In this work we explore whether it is possible to characterise an optimal reverse map building from the concept of state retrieval maps. In doing so, we propose a set of principles that state retrieval maps should satisfy. We find out that the Bayes inspired reverse is just one case in a whole class of possible choices, which can be optimised to give a map retrieving the initial state more precisely than the Bayes rule. Our analysis has the advantage of naturally extending to the quantum regime. In fact, we find a class of reverse transformations containing the Petz recovery map as a particular case, corroborating its interpretation as quantum analogue of the Bayes retrieval. Finally, we present numerical evidences that by adding a single extra axiom one can isolate the usual reverse process derived from Bayes’ theorem.

Entanglement is necessary for Kochen-Specker contextuality in multiqubit systems

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Contextuality demonstrates the non-classicality of single quantum systems. In contrast, entanglement and nonlocality are non-classical phenomena only present in composite systems. However, in this talk I will demonstrate how entanglement and non-locality are essential to Kochen-Specker (KS) contextuality in multiqubit systems. Firstly, we will find that entangled (and, thus, nonlocal) measurements are necessary for state-independent proofs of the KS theorem. Secondly, we will see that state-dependent proofs of the KS theorem which only employ unentangled measurements require a state that is not only entangled but also nonlocal (able to violate a Bell inequality) with respect to projective measurements. Finally, I will discuss the light this result sheds on magic state quantum computation.

Ultrastrong waveguide QED with giant emitters

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Quantum optics with giant emitters has shown a new route for the observation and manipulation of non-Markovian properties in waveguide-QED. In this work we extend the theory of giant atoms, previously restricted to the perturbative light-matter regime, to deal with the ultrastrong coupling regime. Using polaron methods we address the low energy subspace of a giant atom coupled to an ohmic waveguide in this regime. We are able to study the ground state of the system, which shows a photonic cloud around each of the coupling points of the giant emitter with a profile that decays as a power-law. We can also characterize the renormalization of the atomic parameters and the localization-delocalization transition the system can undergo as the coupling increases which shows a dependency on the distance between coupling points. The effects of ultrastrong coupling on the spontaneous emission rate and Lamb shift are also explored as well as the various types of decay processes of this system. Finally we comment on the existence of bound states in this non-perturbative regime.

Robustness of non-locality in many-body open quantum systems

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Non-locality refers to the existence of non-classical correlations between local measurements. So far, it has been investigated mostly in isolated quantum systems. In this work we show that non-local correlations are present, can be detected and might be robust against noise also in many-body open quantum systems, both in the steady state and in the transient regime. We further discuss the robustness of non-local correlations in a setting where the open quantum system undergoes repeated measurements, a scenario which is particularly relevant for quantum cryptography tasks.

Positive maps from the Walled Brauer Algebra

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Starting from the Walled Brauer Algebra, we present matrix inequalities in the Löwner order for variables from the positive cone. These inequalities contain partial transpose and reshuffling operations, and can be understood as positive multilinear maps. In turn, we show that these positive multilinear maps are in one-to-one correspondence with entanglement witnesses showing $U^{\otimes(n-k)} \otimes \bar{U}^{\otimes k}$ invariance.

Optimal fidelity estimation of quantum states on a silicon photonic chip

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As a measure of the “closeness" of two quantum states, fidelity plays an important and fundamental role in quantum information theory. Fidelity estimation protocols try to strike a balance between information gleaned from the experiment, and the efficiency, in terms of the number of states consumed by the protocol. Here we show that, under some reasonable assumptions, the optimal fidelity estimation protocol can be constructed for achieving the minimum-variance estimation of the fidelity, with negligible post-processing. In particular, we present the explicit fidelity estimation strategy for an arbitrary two-qubit state, and experimentally demonstrate the protocol using a fully-programmable silicon photonic two-qubit chip. Our protocol outputs significantly smaller error bars of its point estimate than other estimation protocols, showing a clear step forward in the ability to estimate the fidelity of quantum states produced by a particular device.

Any pair of incompatible rank-one projective measurements is optimal for some non-trivial Bell inequality

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Bell non-locality is an important feature of quantum mechanics as the correlations established among distributed quantum systems are stronger than those allowed by classical physics. In this context, entanglement and incompatibility of measurements [1] are two necessary prerequisites in order to generate non-locality. Here, we show that for a pair of rank-one projective measurements acting on the same finite dimensional space there is a tight connection between non-locality and incompatibility.

Consider two orthonormal bases on C^{d}: $\{e_j\}$ and $\{f_k\}$, and let $\mathrm{O}_{\mathrm{jk}} = |\langle e_j | f_k \rangle|$ represent the overlap between the two bases. In Ref. [2], a Bell functional was constructed and tailored to Mutually Unbiased Bases (MUBs), i.e., assuming that the overlap between the two bases is given by $\mathrm{O}_{\mathrm{jk}} = 1/\sqrt{\mathrm{d}} \ \forall \ \mathrm{j}, \mathrm{k}$. In this work, we generalise this construction to an arbitrary pair of incompatible rank-one projective measurements. Recall that rank-one projective measurements are incompatible if and only if at least one of the overlaps is strictly positive and strictly smaller than one. The following development relies on constructing a family of Bell functionals whose quantum realisation can be obtained from a previously defined Bob's pair of measurements and a suitable choice of Alice's measurements, as well as a proper entangled state. Once the family of functionals is set, novel results can be extracted, as follows.

Result 1. If a pair of rank-one projective measurements is incompatible, then they can be used to generate non-local correlations. Moreover, there exists a non-trivial Bell inequality for which these measurements are optimal. In this content, non-triviality of a Bell inequality means that the quantum value is strictly larger than the local value, forming a gap. Our proof of Result 1 is fully constructive; for every pair of incompatible measurements of Bob we can explicitly construct a functional and show that it is non-trivial. Now, it is natural to ask for which functionals corresponding to measurements acting on C^{d} we have the biggest gap, that is, what is the matrix O of overlaps that maximizes the distance between the quantum and local values?

Result 2. For rank-one projective measurements acting on C^{d} where d is even, the largest gap between quantum and local values is achieved if and only if the rank-one projective measurements correspond to a direct sum of MUBs in dimension 2. In other words, O can be decomposed into 2×2 blocks and all the entries inside these blocks are equal to $1/\sqrt{2}$. Our results significantly improve our understanding of the relation between incompatibility of measurements and Bell non-locality. Moreover, they show that the notion of "the most incompatible measurements" in a given scenario greatly depends on the exact definition of incompatibility.

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Measurement strategies for the Otto engine mediated quantum battery charging

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In the coming age of quantum technology, quantum batteries (QB) will be a core element of energy allocation among different devices. For many practical scenarios, QB chargers would also exhibit their quantum nature, generating analytically intractable non-unitary dynamics. Furthermore, multifarious figures of merits arise for different tasks utilizing QBs. We examine the full energetic picture of the M-level QB charging via a four-stroke two-level Otto engine or refrigerator, tracking work flows, heat flows, and the energy distribution of the battery through numerical simulations. As operationally meaningful measures of valuable energy stored in the battery, its average (internal energy), standard deviation divided by the average (coefficient for variation), and unitarily extractable amount (ergotropy) are assessed. In particular, we employ two different measurement strategies for the QB: one that projectively measures the QB energy at the end of each machine cycle and the other where the battery remains coherent until the end. The effect of periodic decoherence from measurements culminates and produces pronounced differences in all energetic quantities between two models after many cycles. First, we explore the setting where the machine starts as an engine. The former frequent monitoring scheme speeds up both energy and ergotropy accumulations. Yet, the engine performance also deteriorates faster in this case. In the latter strategy, the charging is slow, but the maximum ergotropy storable by engine work output is drastically higher than its counterpart, up to a few orders of magnitude, while internal energies are almost the same for the two. Moreover, the asymptotic state of the battery after many cycles peaks around the highest energy level, contrary to the broader, and thus less beneficial, distribution of periodically measured state. When the charger is initialized as a refrigerator, the advantages of not measuring diminishes. Overall, our results document the role of monitoring schemes in charging QBs, paving the way for measurement frequency engineering to optimize certain aspects of battery performances.

Quantum algorithms for approximate function loading

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Loading classical data into quantum computers represents an essential stage in many relevant quantum algorithms, especially in the field of quantum machine learning. Therefore, the inefficiency of this loading process means a major bottleneck for the application of these algorithms. Here, we introduce two approximate quantum-state preparation methods inspired by the Grover-Rudolph algorithm, which partially solve the problem of loading real functions. Indeed, by allowing for an infidelity ϵ and under certain smoothness conditions, we prove that the complexity of Grover-Rudolph algorithm can be reduced from $\mathrm{O}(2^{\mathrm{n}})$ to $\mathrm{O}(2^{\mathrm{k0}(\epsilon)})$, with n the number of qubits and $\mathrm{k0}(\epsilon)$ asymptotically independent of n. This leads to a dramatic reduction in the number of required two-qubit gates. Aroused by this result, we also propose a variational algorithm capable of loading functions beyond the aforementioned smoothness conditions. Our variational ansatz is explicitly tailored to the landscape of the function, leading to a quasi-optimized number of hyperparameters. This allows us to achieve high fidelity in the loaded state with high speed convergence for the studied examples.

Strong magnon-spin coupling via magnonic vortex quantum cavities

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We explore the coupling of spin emitters to magnonic modes supported by ferromagnetic nanospheres and nanodisks acting as quantum cavities. Employing the formal quantization of the magnetostatic Walker modes for each structure we compute the exact coupling of a spin emitter located at the vicinity of the ferromagnetic cavities, demonstrating that coherent coupling can be achieved in this system. We have compared our theoretical results with numerical simulations based on micromagnetics.

Catalysis in Action via Elementary Thermal Operations

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Catalysts are auxiliary states that interact with the system of interest during a process, and recover their original state afterwards. The benefit of appending such an ancilla has been reported in many frameworks, including quantum thermodynamics. Nevertheless, current results focus mainly on conditions for catalytic advantage. In contrast, the dynamics of catalytic processes have remained unexplored. Moreover, the existing state transition conditions relying on initial and final states, washes out what happens in a continuous-time setting, preventing us from gleaning insight into the potential mechanisms that make a catalyst useful. Motivated by the status quo, we study catalysis in elementary thermal operations (ETO), an experimentally motivated subset of thermal operations, and show that catalysis enhances ETO, which was previously unknown. The structure of ETOs furthermore allow us to trace intermediate steps of the evolution, enabling a study on how system and catalyst explicitly interact with each other. A critical tool we develop is the strengthening of existing upper bounds of computational cost for ETOs, which leads to 1) a full characterization of the three-dimensional system transitions, and 2) computationally tractable numerics for higher dimensions. Interestingly, non-trivial catalyses with exact recovery are found even in the simplest case of a qutrit system and qubit catalyst, fostering experimental implementation together with straightforward operational recipes provided by ETO. Finally, we capture “snapshots” of the catalysis at work, by tracking local free energies of the system-catalyst during evolution. We observed that the system free energy, which always decrease after each ETO, can increase momentarily during the catalytic processes by borrowing catalyst free energies. Our work provides the first analysis of catalysis mechanism occurring in practicable setup, paving the way for a more in-depth understanding of catalytic processes.

Molecular interferometers: effects of Pauli principle on entangled- enhanced precision measurements

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Feshbach molecules forming a Bose–Einstein condensate (BEC) behave as non-ideal bosonic particles due to their underlying fermionic structure. We study the observable consequences of the fermion exchange interactions in the interference of molecular BECs for entangled-enhanced precision measurements. Our many-body treatment of the molecular condensate is based on an ansatz of composite two-fermion bosons which accounts for all possible fermion exchange correlations present in the system. The Pauli principle acts prohibitively on the particle fluctuations during the interference process leading to a loss of precision in phase estimations. However, we find that, in the regime where molecular dissociations do not jeopardize the interference dynamics, measurements of the phase can still be performed with a precision beyond the classical limit comparable to atomic interferometers. We also show that the effects of Pauli principle increases with the noise of the particle detectors such that molecular interferometers would require more efficient detectors.

Inequalities Witnessing Coherence, Nonlocality and Contextuality

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In a recent work, Galvão and Brod described a new graph formalism for studying quantum coherence associated with a set of quantum states. We push further this analysis and study more complex graphs than the ones discussed in Phys. Rev. A 101, 062110. We propose a general algorithm for finding coherence witnesses in the form of linear inequalities for any given fully connected graph, and we find entirely new families of inequalities. Despite this complete characterization for witnessing coherence in terms of inequalities, and the vast literature on coherence as a resource, it is not clear how one can distinguish resources such as coherence and contextuality within the same framework; for instance, there are examples of models that mimic quantum coherence without presenting contextuality or nonlocality, such as the Spekkens toy model from Ref. Phys. Rev. A 75, 032110. Such models proved that coherence may be necessary but not sufficient for stronger forms of nonclassicality, viewed as quantum contextuality and Bell nonlocality, to be present in statistical data. It has even been argued that coherence, in the form of quantum superposition, may be present in similar noncontextual models, and generate interference patterns usually deemed as nonclassical. Understanding what elements of quantum coherence cannot be described by classical models has, therefore, important foundational impact regardless of potential technological applications.

Our work represents a step in characterizing state-of-the-art nonclassicality witnesses of being concomitantly coherent and contextual. Coherence, contextuality and nonlocality are mathematically and conceptually non-equivalent resources. But we show that the inequalities constructed are capable of witnessing all three of these resources given different quantum realizations and conceptual interpretations allowed by our graph formalism. We prove that, in particular, we can select, by operating over specific graph scenarios, all the inequalities in the Cabello-Severini-Winter framework for Kochen-Specker contextuality. We also argue that the single system Spekkens Toy Model does not violate our inequalities. Specifically for viewing these graphs as coherence-witnessing scenarios, we have shown an infinite new family of inequalities that are capable of witnessing coherence. A large classification and analysis of quantum violations is also presented.

The inequalities presented here are experimentally accessible, and were already violated experimentally in Ref. Phys. Rev. Research 3, 023031 and we speculate that our inequalities can also serve as witnesses for robust forms of nonclassicality not only for coherence but also for contextuality. We are still trying to understand if these inequalities can be understood as robust noncontextuality inequalities in particular scenarios, or as inequalities bounding generalized noncontextuality. It is possible that these inequalities may give insights for future new resource theories of coherence and new tests of generalized contextuality without tomographically complete loophole, but such perspective is still of speculative nature.

This is joint work together with Ernesto Galvão and Rui Soares Barbosa.

Study of the definitions of heat and work in cavity QED

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The very concepts of heat and work in quantum thermodynamics have been the cornerstone in the development of such theory. Since the original definitions of Alicki [1], many have pointed out the necessity of brand new interpretations, given the evolution of theoretical and technological research [2]. In this direction, we study the concepts of work and heat by means of a prototypical model in QED, the Jaynes-Cummings model, and we compare our results with the established definitions. In the model, as in classical thermodynamics, one wall of the cavity moves due to the pressure generated within it, showing how radiation pressure can generate a non-zero amount of work. Finally, we apply the fundamentals of the aforementioned model to build a Quantum Otto Engine and explore the main thermodynamic parameters.

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Understanding the role of quantum measurements in thermodynamic uncertainty relations

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Quantum stochastic thermodynamics is a burgeoning field, and is providing many deep insights into the nature of thermodynamics at the quantum scale. At its core lies the role of measurement, which by definition leads to stochastic outcomes on observed thermodynamics quantities. Here we are interested in thermodynamic properties of mesoscopic systems subject to continuous quantum measurements, and their properties. In particular, we study the thermodynamic uncertainty relation (TUR) which bounds the measured signal to noise ratio of any observed current, by the inverse of the entropy production. We study this in a prototypical set up consisting of a quantum dot coupled to two reservoirs. To this end, we are interested in relating observed outcomes to the power spectrum and the entropy production rate, using both a stochastic thermodynamics approach and a trajectory based approach. We further seek to understand the validity of the lower bound of the TUR in the presence of quantum measurements, which has been shown to be violated in many quantum systems.

Quantum value for a family of I3322-like Bell functionals

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We introduce a three-parameter family of Bell functionals that extends those studied in reference [Phys. Rev. Research 2, 033420 (2020)] by including a marginal contribution. An analysis of their quantum value naturally splits the family into two branches, and for the first of them we show that this value is given by a simple function of the parameters defining the functionals. In this case we completely characterise the realisations attaining the optimal value and show that these functionals can be used to self-test any partially entangled state of two qubits. The optimal measurements, however, are not unique and form a one-parameter family of qubit measurements. The second branch, which includes the well-known I3322 functional, is studied numerically. We identify the region in the parameter space where the quantum value can be attained with two-dimensional systems and characterise the state and measurements attaining this value. Finally, we show that the set of realisations introduced in reference [Phys. Rev. A 82, 022116 (2010)] to obtain the maximal violation of the I3322 inequality succeeds in approaching the optimal value for a large subset of the functionals in this branch. In these cases we analyse and discuss the main features of the optimal realisations.

A single entanglement measure built using a geometric approach unifying several known entanglement measures

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Entanglement, and quantum correlations, are precious resources for quantum technologies implementation based on quantum information science, as, for instance, quantum communication, quantum computing, quantum sensing, and quantum complex systems. Nevertheless, a directly computable measure for the entanglement either of multipartite pure or mixed states is still lacking. Here, we propose a measure of entanglement for pure states, based on the Fubini-Study metric defined in the projective Hilbert space, and a measure of quantum correlations for mixed states, based on the Hilbert Schmidt distance defined in the space of density matrices. The measures are invariant under local unitary transformations and have an explicit computable expression that we derive. In the specific case of pure qubit systems, the measure assumes the physical interpretation of an obstacle to the minimum distance between infinitesimally close states.

The Geometry of Composite Systems: Bloch-Ball Analog for Two Qubits

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An essential tool for developing knowledge in many concepts of physics is geometric intuition. In quantum mechanics, the most known example is the Bloch sphere for a two-level (qubit) system. Systems of higher dimension $d > 2$, such as two qubits (with $d = 4$), need a representation in a $(d^2 - 1)$-dimensional space to have a complete description of the system. The geometric object that describes the two-qubit system has a much richer structure and is more representative of the general Bloch ball object than the qubit representation. In this work, based on the Bloch representation, we construct a three-dimensional model for the correlation part of the state space that captures essential geometric features of the object. The work provides, on the one hand, examples for simple algebraic constraints on quantifiers of correlations, and, on the other hand, opens the door for new geometric representations of correlations in composite systems.

Preserving quantum correlations and coherence with non-Markovianity

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We demonstrate, both analytically and experimentally, the usefulness of non-Markovianity for preserving correlations and coherence in quantum systems. For this, we consider a broad class of qubit evolutions, having a decoherence matrix separated from zero for large times. While any such Markovian evolution leads to an exponential loss of correlations, non-Markovianity can help to preserve correlations even in the limit $t \to \infty$. In fact, under general assumptions, eternally non-Markovian evolution naturally emerges as the one that allows for optimal preservation of quantum correlations. For covariant qubit evolutions, we also show that non-Markovianity can be used to preserve quantum coherence at all times, which is an important resource for quantum metrology. We explicitly demonstrate this effect experimentally with linear optics, by implementing the optimal non-Markovian quantum evolution.

Two-colour high-purity Einstein-Podolsky-Rosen photonic state

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Entanglement is the backbone of quantum information science and its applications. Entangled states of light are necessary for distributed quantum protocols, quantum sensing and quantum internet. A distributed quantum network requires entanglement between light modes of different colour optimized for interaction with the nodes as well as for communication between them. Here we demonstrate high-purity Einstein-Podolsky-Rosen (EPR) entangled state between light modes with the wavelengths separated by more than 200 nm. The modes display −7.7 ± 0.5 dB of two-mode entanglement and an overall state purity of 0.63 ± 0.16. Entanglement is observed over five octaves of sideband frequencies from rf down to audio-band. In the context of two-colour entanglement, the demonstrated combination of high state purity, strong entanglement, and extended frequency range paves the way to new matter-light quantum protocols, such as teleportation between disparate quantum systems, quantum sensing and quantum enhanced gravitational wave interferometry. The scheme demonstrated here can be readily applied towards entanglement between telecom wavelengths and atomic quantum memories.

Entropy Production at Zero Temperature

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Fluctuation theorems allow one to make generalised statements about the behaviour of thermodynamic quantities in systems that are driven far from thermal equilibrium. In this talk, I'll present our recent results where we use Crooks' fluctuation theorem to understand the entropy production of a continuously measured, zero-temperature quantum system; namely an optical cavity measured via homodyne detection. At zero temperature, if one uses the classical definition of inverse temperature then the entropy production becomes divergent. Our analysis shows that the entropy production can be well defined at zero temperature by considering the entropy produced in the measurement record. We link this result to the Cramer-Rao inequality and show that the product of the Fisher information in the work distribution with the entropy production is bounded below by the square of the inverse energy fluctuations. This inequality indicates that there is a minimal amount of entropy produced in acquiring information about the work done to a quantum system driven far from equilibrium via quantum measurement. In this talk, I will present a pedagogical derivation of this result and argue that thermodynamics quantities should be best understood through the lens of quantum measurements, and the associated fluctuations in these quantum measurement records.

Logically consistent causal structures

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Time has always been a fundamental concept in physics and philosophy and the debate over its understanding has always played a central role in the progress of science. Being at the core of every physical theory, the ordering of the events and subsequently the direction of time, carries implicit assumptions that make the study of time within the physical theories difficult, as no independent statement can be made. Shortly after the birth of General Relativity, dynamics that described Closed Time-like Curves (CTCs), i.e. time-travelling scenarios, a situation where A is the cause of B and at the same time B is the cause of A, were found by Laszcos and Gödel independently. This self-reference problem has made such scenarios reprehensible to the scientific community as logical consistency, the foundation of the scientific language, seemed to be endangered. It was only, though, during the last decade that Brukner et al. established an operational non-causal theory, by relaxing the global notion of time between observers (usually referred to as the process matrix formalism). This interventional formalism does not suffer from logical inconsistencies, while at the same time provides non-trivial examples of CTCs, from the Quantum Information Theory perspective.

In this poster/talk I will present the admissible, according to the minimal constraint of logical consistency, signalling relations that agents can be connected with. I will categorise them in 3 main categories, the causal, the causally non-separable (an analogous notion of entanglement and separability but in communication scenarios) and further divide the latter into two, the ones that can potentially violate causal inequalities* and those that do not. The treatment of this subject is done both in the classical and quantum case.

*Causal inequalities refer to a No-Go theorem the violation of which indicates, in a device-independent way, the incompatibility of explaining/simulating correlations beyond these constraints/bounds with a well-defined ordering of the interventions of the parties.

Quantum Spread Spectrum for Transmission Security (TRANSEC) in Tactical Communications

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Quantum communications can be used to address the growing electronic warfare capabilities of peer and near-peer adversaries in hostile environments with Anti-Access/Area Denial in which the freedom of maneuver in the electromagnetic spectrum will be contested. By means of Electronic Attack, the opponent will try to detect, intercept and jam our communications.

Transmission security of single-photon quantum states can be improved by using spread spectrum communication techniques.

At this regard, Quantum Spread Spectrum by spreading the spectral bandwidth of the photon carrier beyond the information bandwidth can be used for Transmission Security. Since it safeguard transmissions against interception (Low Probability of Interception, LPI) and detection (Low Probability of Detection, LPD), and precludes enemy to disrupt communications (Anti-Jamming).

Spread spectrum techniques include Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) or mix of both techniques (FH/DS).

It's proposed to deploy DSSS technique employed to single photons. First, it's spread the photon’s spectral state with the help of a code, and then despread at the receiver side by again multiplying the signal by the same value of the code. In despreading operation, we get back the photon’s spectral state in original form, detecting single-photon spectral state.

Narrowband photons may be phase modulated in order to broaden their spectrum by several orders of magnitude, thus reducing the spectral power density, while at the same time retaining the information that characterizes their waveform. Therefore, the resulting waveform can be transmitted through a hostile environment (background noise and/or jamming).

The photon is frequency-spread by the modulator, to hide the photons in the background noise and provide covertness communications. Spectrum of the information photons can increase and thus experiencing a processing gain. So the classical concept of spread spectrum can be applied to single photon.

The advantage of such systems is LPI, LPD, and resistance to jamming and interference. Since a broad spectral bandwidth signal is more difficult to distinguish from environment noise, which adds to the security of the channel (TRANSEC).

Undecidability in resource theory: can you tell theories apart?

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A central question in resource theory is whether one can construct a set of monotones that completely characterise the allowed transitions dictated by a set of free operations. A similar question is whether two distinct sets of free operations generate the same class of transitions. These questions are part of the more general problem of whether it is possible to pass from one characterisation of a resource theory to another. In the present letter we prove that in the context of quantum resource theories this class of problems is undecidable in general. This is done by proving the undecidability of the membership problem for CPTP maps, which subsumes all the other results.

Universal distributed quantum gates in microwave links

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We propose a realistic setup, inspired by already existing experiments, within which we develop a general formalism for the implementation of distributed quantum gates. Mediated by a quantum link that establishes a bidirectional quantum channel between distant nodes, our proposal works both for inter- and intranode communication and handles scenarios ranging from the few to the many modes limit of the quantum link. We are able to design fast and reliable state transfer protocols in every regime of operation, which, together with a detailed description of the scattering process, allows us to engineer two sets of deterministic universal distributed quantum gates. Gates whose implementation in quantum networks does not need entanglement distribution nor measurements. By employing a realistic description of the physical setup we identify the most relevant imperfections in the quantum links as well as optimal points of operation with resulting fidelities of 99 to 99.9%.

Non-Abelian Quantum Transport and Thermosqueezing Effects

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Modern quantum experiments provide examples of transport with noncommuting quantities, offering a tool to understand the interplay between thermal and quantum effects. Here we set forth a theory for non-Abelian transport in the linear response regime. Our key insight is to use generalized Gibbs ensembles with noncommuting charges as the basic building blocks and strict charge-preserving unitaries in a collisional setup. The linear response framework is then built using a collisional model between two reservoirs. We show that the transport coefficients obey Onsager reciprocity. Moreover, we find that quantum coherence, associated with the noncommutativity, acts so as to reduce the net entropy production, when compared to the case of commuting transport. This therefore provides a clear connection between quantum coherent transport and dissipation. As an example, we study heat and squeezing fluxes in bosonic systems, characterizing a set of thermosqueezing coefficients with potential applications in metrology and heat-to-work conversion in the quantum regime.

Quantum Genetic Algorithm

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Genetic algorithms are heuristic optimization techniques inspired by Darwinian evolution, which are characterized by successfully finding robust solutions for optimization problems. In this talk, I present a subroutine-based quantum genetic algorithm with individuals codified in independent registers. This distinctive codification allows our proposal to depict all the fundamental elements characterizing genetic algorithms, i.e. population-based search with selection of many individuals, crossover, and mutation. Our subroutine-based construction permits us to consider several variants of the algorithm. For instance, we analyze the performance of two different quantum cloning machines, a key component of the crossover subroutine. Furthermore, we introduce a quantum channel analysis to prove the exponential convergence of our algorithm and even predict its convergence-ratio. This tool could be extended to formally prove results on the convergence of general non-unitary iteration-based algorithms.

Contextuality and memory cost of simulation of Majorana fermions

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Contextuality has been reported to be a resource for quantum computation, analogous to non-locality which is a known resource for quantum communication and cryptography. We show that the presence of contextuality places new lower bounds on the memory cost for classically simulating restricted classes of quantum computation. We apply this result to the simulation of a model of quantum computation based on the braiding of Majorana fermions, namely topological quantum computation (TQC) with Ising anyons, finding a saturable lower bound in log-linear in the number of physical modes for the memory cost. TQC model lies in the intersection between two computational models: the Clifford group and the fermionic linear optics (FLO), a framework analogous to bosonic linear optics. We extend our results and prove that the lower bound in the memory required in an approximate simulation of the FLO model is quadratic in the number of physical modes.

Device-independent certification of maximal randomness from pure entangled two-qutrit states using non-projective measurements

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While it has recently been demonstrated how to certify the maximal amount of randomness from any pure two-qubit entangled state in a device-independent way [E. Woodhead et al., Phys. Rev. Research 2, 042028(R)(2020)], the problem of optimal randomness certification from entangled states of higher local dimension remains open. Here we introduce a method for device-independent certification of the maximal possible amount of 2log23 random bits using pure bipartite entangled two-qutrit states and extremal nine-outcome general non-projective measurements. To this aim, we exploit the extended Bell scenario introduced recently in [S. Sarkar et al., arXiv:2110.15176], which combines a device-independent method for certification of the full Weyl-Heisenberg basis in three-dimensional Hilbert spaces together with a one-sided device-independent method for certification of two-qutrit partially entangled states.

Quantum associative memory with single driven-dissipative oscillator

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Algorithms for associative memory typically need a network of many connected systems. The prototypical example is the Hopfield model, whose generalisations to the quantum realm are mainly based on multipartite open quantum systems. We propose a model of associative memory with a single driven-dissipative quantum system exploiting its infinite degrees of freedom in phase space. We prove that the model is able to distinguish among n coherent states, which represent the stored patterns of the system. These can be tuned continuously by modifying the driving and dissipation strength, constituting a modified learning rule. We show that the associative-memory capacity is inherently related to the existence of a spectral gap in the Liouvillian superoperator, which results in a large time-scale separation in the dynamics corresponding to a metastable phase. There, a near-unit success probability is achieved, even for a single trajectory.

A graph state construction of S_n-invariant subspaces in the multipartite Schur-Weyl decomposition

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The invariant subspace of the tensor product of three or more irreducible representations of the symmetric group is a powerful source of multipartite entangled states that are useful in quantum information. We propose a procedure to explicitly construct such invariant states, which we term *Kronecker states*, based on a correspondence with a graphic PEPS representation of entangled multiqubit states, where the vertices are tripartite W states. Applying the Schur-Weyl decomposition to n copies of the graph state, we can associate each graph with a family of Kronecker graph states, where the vertices are certain fundamental “W-class" Kronecker states. We explore the correspondence that exists between the topology of a given graph (e.g., the number of loops) and the span of the Kronecker states associated to it.

Circuit compilation and hybrid computation using Pauli-based computation

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Pauli-based computation (PBC) is driven by a sequence of adaptively chosen, non-destructive measurements of Pauli observables BSS16. Any quantum circuit written in terms of the Clifford+T gate set and having t T gates can be compiled into a PBC on t qubits. We propose practical ways of implementing PBC as adaptive quantum circuits, and provide code to do the required classical side-processing. Our first scheme reduces the number of quantum gates to $O(t^2)$ (from a previous $O(t^3)$ / log t scaling Yoga19 at the cost of one extra auxiliary qubit, with a possible reduction of the depth to $O(t)$ / log t at the cost of t additional auxiliary qubits (second scheme). We compile examples of random and hidden-shift quantum circuits into adaptive PBC circuits. We also simulate hybrid quantum computation, where a classical computer effectively extends the working memory of a small quantum computer by k virtual qubits, at a cost exponential in k. Our results demonstrate the practical advantage of PBC techniques for circuit compilation and hybrid computation.

We expect this work to be relevant both in the near term and in the long term. Firstly, PBC compilation allows the efficient reduction of intermediate-sized quantum circuits into smaller instances that can be run on current or near-term quantum hardware. Secondly, this reduction of quantum resources (i.e. number of qubits, depth and/or gate counts) will remain relevant even when large-scale, fault-tolerant quantum computers become available. Finally, hybrid PBC might be of particular interest for supercomputing centers wherein the powerful, available classical machines can be used to extend the working memory of a small QPU.

(E-print at https://arxiv.org/abs/2203.01789 and Python code at https://github.com/fcrperes/CompHybPBC.)

Time-frequency as quantum continuous variables

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We present a second quantization description of frequency-based continuous variables quantum computation in the subspace of single photons. For this, we define frequency and time operators using the free field Hamiltonian and its Fourier transform, and show that these observables, when restricted to the one photon per mode subspace, reproduce the canonical position-momentum com- mutation relations. As a consequence, frequency and time operators can be used to define a universal set of gates in this particular subspace. We discuss the physical implementation of these gates as well as their effect on single photon states, and show that frequency and time variables can also be used to implement continuous variables quantum information protocols, in the same way than polarization is currently used as a two-dimensional quantum variable.

Hardware-efficient entangled measurements for variational quantum algorithms

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Variational algorithms have received significant attention in recent years due to their potential to solve practical problems in noisy intermediate-scale quantum (NISQ) devices. A fundamental step of these algorithms is the evaluation of the expected value of Hamiltonians, and hence, efficient schemes to perform this task are required. The standard approach employs local measurements of Pauli operators and requires a large number of circuits. An alternative is to make use of entangled measurements, which significantly reduces the number of circuits but involves entangling gates between non-physically connected qubits, introducing intermediate entangling operations that increase the depth of the circuits.

In this talk I will explain our proposal to solve this problem: hardware-efficient entangled measurements (HEEM), that is, measurements that only permit entanglement between physically connected qubits. I will show that our strategy enhances the evaluation of molecular Hamiltonians in NISQ devices, reducing the number of circuits required without increasing their depth.

Keeping track of the concentrations in nanoscale samples with NV centers

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We develop a formalism that combines control fields over a nitrogen vacancy (NV) center with the continuous harvesting of the NV delivered data to detect quantities such as half-life in radioactive decay, or reagents concentration in a chemical reaction involving, e.g., free-radicals. In this scenario, the measured quantities –e.g. the concentration of unstable isotopes, as well as the newborn products in a nuclear decay– changes during the detection process, thus we have developed a method based on Bayesian inference to appropriately deal with the experimentally collected data.

Noisy Atomic Magnetometry in Real-Time

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Continuously monitored atomic spin-ensembles allow, in principle, for real-time sensing of external magnetic fields beyond classical limits. Within the linear-Gaussian regime, thanks to the phenomenon of measurement-induced spin-squeezing, they attain a quantum-enhanced scaling of sensitivity both as a function of time, t, and the number of atoms involved, N.

In our work, we rigorously study how such conclusions based on Kalman filtering methods change when inevitable imperfections are taken into account: in the form of collective and local decoherence, as well as stochastic fluctuations of the field in time. We prove that even an infinitesimal amount of noise disallows the error to be arbitrarily diminished by simply increasing N, and forces it to eventually follow a classical-like behaviour in t.

However, we also demonstrate that, “thanks” to the presence of collective noise, in most regimes the model based on a homodyne-like continuous measurement actually achieves the ultimate sensitivity allowed by the collective decoherence, yielding then the optimal quantum-enhancement. We are able to do so by constructing a noise-induced lower bound on the error that stems from a general method of classically simulating a noisy quantum evolution, during which the stochastic parameter to be estimated -- here, the magnetic field -- is encoded. The method naturally extends to schemes beyond the linear-Gaussian regime, in particular, also to ones involving feedback or active control.

A quantum walk simulation of extra dimensions with warped geometry

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Poster

We investigate the properties of a quantum walk which can simulate the behavior of a spin 1/2 particle in a model with an ordinary spatial dimension, and one extra dimension with warped geometry between two branes. Such a setup constitutes a 1+1 dimensional version of the Randall-Sundrum model, which plays an important role in high energy physics. In the continuum spacetime limit, the quantum walk reproduces the Dirac equation corresponding to the model, which allows to anticipate some of the properties that can be reproduced by the quantum walk. In particular, we observe that the probability distribution becomes, at large time steps, concentrated near the "low energy" brane, and can be approximated as the lowest eigenstate of the continuum Hamiltonian that is compatible with the symmetries of the model. In this way, we obtain a localization effect whose strength is controlled by a warp coefficient. In other words, here localization arises from the geometry of the model, at variance with the usual effect that is originated from random irregularities, as in Anderson localization. In summary, we establish an interesting correspondence between a high energy physics model and localization in quantum walks.

Quantum simulation and machine learned analysis of the Agassi model

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Quantum simulations provide a fast-developing and powerful tool to realize the analysis of various physical systems of quantum nature and should be able to outperform classical computers and solve previously intractable problems. As such, many experimental setups are being proposed to validate the feasibility of the quantum simulation of different physical models. One prominent many-body quantum system in Nuclear Physics is the Agassi model, which is a two-level system that includes a combination of long range monopole-monopole and short range pairing interactions. An extended Agassi model that adds a more general pairing interaction, presents a very rich quantum phase diagram that gives rise to several quantum phase transitions (QPTs) of different character, making it of great interest in the field of QPTs. In this talk, we will present this model and propose an experimental setup for its quantum simulation. We will then apply machine learning tools to check the information that could be extracted from its simulation.

Entanglement scaling in long-time evolution of matrix product states for quantum chains

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We present some results of our investigation of the long-time evolution of one-dimensional quantum chains after quenches across a critical point. We employ tensor-network techniques and focus on the scaling properties of the entropy as we vary the simulation parameters for the evolution of our matrix product states.

Multicopy metrology with many-particle quantum states

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In [1], we consider quantum metrology with several copies of bipartite and multipartite quantum states. We identify a large class of entangled states that become maximally useful for metrology in the limit of infinite number of copies. The maximally achievable metrological usefulness is attained exponentially fast in the number of copies. We show that, on the other hand, pure entangled states with even a small amount of white noise do not become maximally useful even in the limit of infinite number of copies. We also make general statements about the usefulness of a single copy of pure entangled states. We show that the multiqubit states presented in Hyllus et al. [Phys. Rev. A 82 , 012337 (2010)], which are not more useful than separable states, become more useful if we embed the qubits locally in qutrits. We discuss the relation of our scheme to error correction, and possible use for quantum information processing in a noisy environment.

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Characterizing (Non-)Markovianity through Fisher Information

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A non-isolated physical system typically loses information to its environment, and when such loss is irreversible the evolution is said to be Markovian. Non-Markovian effects are studied by monitoring how information quantifiers, such as the distance between physical states, evolve in time. Here we show that the Fisher Information metric emerges as the natural object to study in this context; we fully characterize the relation between its contractivity properties and Markovianity, both from the mathematical and operational point of view.

We prove, both for classical and for quantum dynamics, that Markovianity is equivalent to the monotonous contraction of the Fisher metric at all points of the set of states. At the same time, operational witnesses of non-Markovianity based on the dilation of the Fisher distance cannot, in general, detect all non-Markovian evolutions, unless specific physical postprocessing is applied to the dynamics. Finally, we show for the first time that non-Markovian dilations of Fisher distance between states at any time correspond to backflow of information about the initial state of the dynamics at time 0, via Bayesian retrodiction.

Hidden nonlocality in broadcasting Bell scenarios

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It is interesting to identify whether a quantum state is entangled or not in a device-independent way (meaning that we only have access to the statistics of the measurement results and we assume nothing about the measurement apparatus or the quantum state). It is known that if the measurement statistics violate a Bell inequality then this certifies entanglement, however some mixed bipartite entangled states cannot violate any Bell inequality. One such example is the two-qubit Werner state, $\alpha|\phi^+\rangle\langle\phi^+| + (1-\alpha)\mathbb{I}/4$ which for $1/3 < \alpha < 0.683$ is entangled while also having a local hidden variable model. One then would like to find device-independent entanglement certification techniques that can certify entanglement for states such as these.

One such recent technique is the “broadcasting” technique, which uses a single copy of the quantum state. In the standard Bell scenario we have only two parties, Alice and Bob. An example of a broadcasting scenario is one where Bob applies any desired quantum channel to his part of the quantum state and then distributes/broadcasts it to his friends Bob1 and Bob2 that perform local measurements on the state they received. This then is a mapping from a bipartite Bell scenario (Alice,Bob) to a multipartite Bell scenario (Alice,Bob1,Bob2) where a violation of a carefully defined multipartite inequality certifies entanglement in the original bipartite scenario.

In this work we focus on the broadcasting scenario and show through semidefinite programming techniques that device-independent entanglement certification is possible for the two-qubit Werner state in essentially the entire range of entanglement ($\alpha > 0.338$). Furthermore, we construct Bell inequalities tailored to the broadcast scenario, and show how broadcasting can lead to even stronger notions of Bell nonlocality activation. In particular, we exploit these ideas to show that bipartite states admitting a local hidden-variable model for general (POVM) measurements can lead to genuine tripartite nonlocal correlations. Finally, we extend the concept of EPR steering to the broadcast scenario, and present novel examples of activation of the two-qubit isotropic state.

https://arxiv.org/abs/2111.06358

Quantum transfer between arbitrary pairs of protected states in a topological ladder

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In recent years, the number of proposed quantum protocols which use the protected end states of topological insulators has increased steadily [1-4]. Most of them, however, are constrained by two limitations: the transfer can only happen between the ends of the system, and the time it takes to be completed scales exponentially with distance.

We explore solutions to these issues by proposing a family of quantum transfer protocols between any two topological states in a quasi-1D topological insulator: the multi-domain Creutz ladder.

This model can have an arbitrary number of topological modes. Each of its domain walls holds two such states, which can be tuned with a control parameter [5]. This is possible due to the interference created by the magnetic field, which is also responsible for the flat bands of the model. In our work [6], we describe its topological subspace in detail, propose the transfer protocols mentioned above, and discuss some applications in the field of quantum information.

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Random access codes via quantum contextual redundancy

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We propose a protocol to encode classical bits in the measurement statistics of a set of parity observables, leveraging quantum contextual relations for a random access code task. The intrinsic information redundancy of quantum contexts allows for a posterior decoding protocol that requires few samples when encoding the information in a set of highly entangled states, which can be generated by a discretely-parametrized quantum circuit.

Applications of this protocol include algorithms involving storage of large amounts of data but requiring only partial retrieval of the information, as is the case of decision trees.

This classical-to-quantum encoding is a compression protocol for more than 18 qubits and shows quantum advantage over state-of-the-art information storage capacity for more than 44 qubits. In particular, systems above 100 qubits would be sufficient to encode a brute force solution for games of chess-like complexity.

Matter in non-perturbative cavity QED

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Starting from a general material system of N particles coupled to a cavity, we use a coherent state path integral formulation to produce a non-perturbative effective theory for the material degrees of freedom. The resulting (non-local) action has the photonic degrees of freedom replaced by an effective position-dependent interaction between the particles. In the large-N limit, we discuss how the theory can be cast into an effective Hamiltonian where the cavity induced interactions are made explicit [1].

We apply the theory to a system of magnetic molecules coupled to microwave cavities (LC resonators). The cavity is shown to mediate potentially significant ferromagnetic interactions between the molecules. This effect is illustrated by the modification of the magnetic phase diagram of dipolar crystals, exemplifying the cooperation between intrinsic and photon-induced spin-spin interactions in experimentally accessible settings. This can also be understood as an equilibrium superradiant phase transition (SPT). The (parity) symmetry is spontaneously broken leading to ferromagnetic order in the “matter" and to a nonzero population of photons in the cavity at equilibrium [2].

Finally, we discuss the experimental setup required to produce and measure the quantum electrodynamical control of magnetic crystals.

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Development of NbTiN superconducting resonators for quantum technologies

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NbTiN thin films have recently demonstrated advantageous properties over traditional superconductors such as Nb and Al for superconducting quantum applications. For instance, it has higher Tc and a very high upper critical field, allowing maintaining high internal quality factors even in presence of high magnetic fields.

We present our work on developing NbTiN superconducting lumped element resonators (LERs). Each LER consists of a series inductance-capacitance circuit coupled in parallel to a single transmission line. Contrary to coplanar wave resonators, LERs allow large freedom in the geometry design, which enables to control of key parameters such as the quality factor and the induced field volume. In addition, LERs are intrinsically multiplexable on-chip, which allows the simultaneous readout of several qubits at different frequencies. These types of resonators are crucial elements in many quantum applications such as quantum electrodynamics circuitry, quantum sensing, and astronomy detectors. Lumped Element superconducting Resonators (LERs)

We will show the NbTiN nanofabrication optimization based on a reactive DC sputtering process of nitrogen and argon gases and a high-quality NbTi target. As obtained for the results, pressure and power are the main parameters to be optimized during the deposition process.

Based on these films, we have fabricated and tested a chip containing twelve LERs. Using a calibration protocol developed for a proper IQ cryogenic characterization, we will show the temperature and power dependence of the developed LERs. The obtained quality factors of over 1 million probe the good performance of these devices and open the possibility of their application in quantum technologies as highly sensitive detectors for quantum communications or as basic building blocks for molecular spin qubits or gatemon qubits.

This work was supported by Spanish Ministry of Science and Innovation under Grant PID2019-105552RB, Grant SEV-2016- 0686 and ONR-Global through Grant DEFROST N62909-19-1-2053. This project has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862893 (FATMOLs). We also acknowledge support from CSIC Research Platform PTI-001