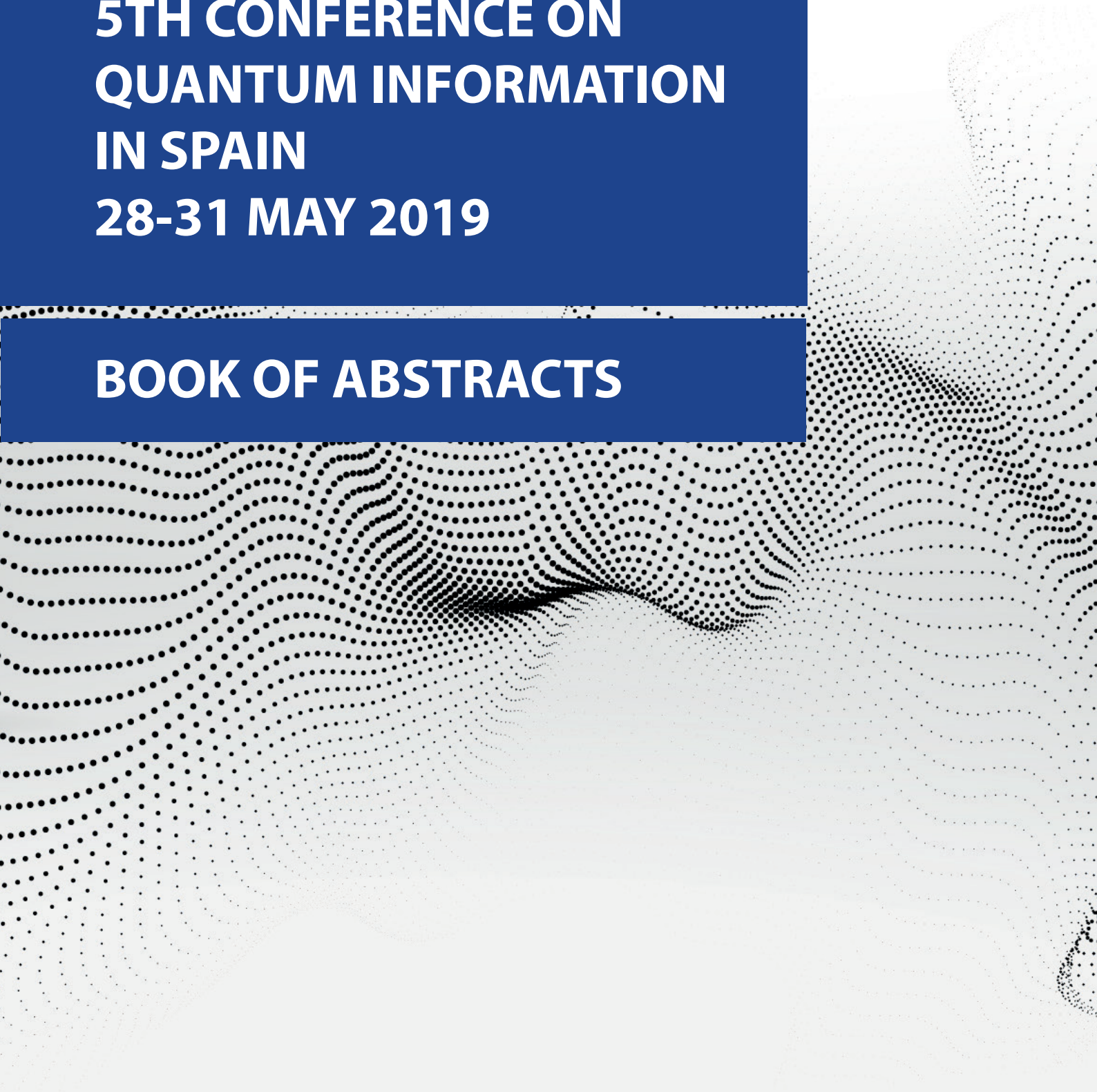
ICE-5
5TH CONFERENCE ON QUANTUM INFORMATION IN SPAIN
28-31 MAY 2019

BOOK OF ABSTRACTS



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PROGRAM

Tuesday, 28th May

09:00 - 09:15 **Welcome**

09:15 - 10:00 **Generation of quantum light in a photon-number superposition**
Pascale Senellart, *CNRS, Institut de Recherche de Chimie Paris*

10:00 - 10:30 **Long-lived nuclear spins in rare-earth doped Y2O3 nanoparticles**
Diana Serrano, CNRS, Institut de Recherche de Chimie Paris

10:30 - 11:00 **Low-cost error mitigation by symmetry verification**
Xavier Bonet Monroig, Universiteit Leiden

11:00 - 11:30 **Coffee break**

11:30 - 12:15 **Spectral gap in PEPS**
David Pérez-García, Universidad de Valencia

12:15 - 12:45 **Finite correlation scaling in projected entangled paired states**
Luca Tagliacozzo, University of Barcelona

12:45 - 13:15 **Predicting the robust features of the out-of-equilibrium evolution of many-body quantum systems**
Jacopo Surace, University of Strathclyde

13:15 - 14:45 **Lunch break**

14:45 - 15:30 **Quantum optics and simulation with topological photons**
Alejandro González-Tudela, CSIC

15:30 - 16:00 **Bounding correlations in quantum causal networks**
Alejandro Pozas-Kerstjens, ICFO

16:00 - 18:00 **Poster session**

Wednesday, 29th May

09:15 - 10:00 **Quantum algorithm enhanced quantum sensing**
Joerg Wrachtrup, University of Stuttgart

10:00 - 10:30 **Refuting observer dependence in quantum theory**
Alessandro Fedrizzi, Heriot-Watt University

10:30 - 11:00 **Hot, dense atomic media for measurement-based quantum optical technologies**
Jia Kong, ICFO

11:00 - 11:30 **Coffee break**

11:30 - 12:15 **Towards implementation security of quantum cryptography**
Marcos Curty, University of Vigo

12:15 - 12:45 **Plug-and-play continuous variable quantum key distribution system with a true local oscillator**
Sebastian Etcheverry, Stockholm University

12:45 - 13:15 **Entanglement Between a Photonic Time-Bin Qubit and a Collective Atomic Spin Excitation**
Pau Farrera, ICFO

13:15 - 14:45 **Lunch break**

14:45 - 15:30 **Even nanoparticles get the entanglement**
Gabriel Molina-Terriza, Donostia International Physics Center

15:30 - 16:00 **Quantum devices outperforming classical computers**
Juani Bermejo-Vega, Free Univeristy of Berlin

16:00 - 16:30 **Verification of Quantum Optimizers**
Flavio Baccari, ICFO

16:30 - 17:30 **RITCE Meeting**

Thursday, 30th May

9:15 - 10:00 **Solitons, droplets and density-dependent gauge fields in two component Bose-Einstein condensates**
Leticia Tarruell, ICFO

10:00 - 10:30 **Quantum entanglement study of the two-component Bose-Hubbard model**
Ivan Morera Navarro, University of Barcelona

10:30 - 11:00 **A resource theory of entanglement with a unique multipartite maximally entangled state**
Julio De Vicente, Universidad Carlos III de Madrid

11:00 - 11:30 **Coffee break**

11:30 - 12:15 **Single-Shot Quantum Statistical Inference: Change-point and anomaly detection & generalized swap-test**
John Calsamiglia, University of Barcelona

12:15 - 12:45 **Unsupervised classification of quantum data**
Gael Sentís, University of Siegen

12:45 - 13:15 **Using and reusing coherence to realize quantum processes**
Matteo Rosati, University of Barcelona

13:15 - 14:45 **Lunch break**

14:45 - 15:30 **Scaling up quantum computing with magnetic molecules**
Fernando Luis, CSIC

15:30 - 16:00 **Limits on spectral resolution measurements by quantum probes**
Javier Prior, Universidad Politécnica de Cartagena

16:00 - 16:30 **The Trapsensor facility: precision experiments in Penning traps with a single laser-cooled 40Ca+ ion as a detector**
Francisco Domínguez, University of Granada

INVITED SPEAKERS

Generation of quantum light in a photon-number superposition

Pascale Senellart, *CNRS Centre for Nanoscience and Nanotechnology, Université Paris-Sud, Université Paris-Saclay, 91120 Palaiseau, France*

The ability to generate light in pure quantum states is central to the development of quantum- enhanced technologies. Recently, artificial atoms in the form of semiconductor quantum dots have emerged as an excellent platform for quantum light generation [1-2].

By placing the quantum dot in an optical microcavity, pure dephasing phenomena are strongly suppressed and single photon wavepackets with very high quantum purity in the frequency domain are generated. This is demonstrated at unprecedented high rate and it allows to scale up linear quantum optical technologies [3-4].

The system is also shown to generate light pulses in a pure quantum superposition in the photon number basis, a feature that has never been demonstrated even with natural atoms. This is obtained through coherent control of the artificial atom transition: a pure quantum superposition of vacuum and one-photon is generated with a full control of their relative populations. Driving the system even stronger, a coherent superposition of vacuum, one- and two-photons is generated, with the two-photon part exceeding the one- photon part---a state that shows phase super-resolving interferometry. Our experimental demonstration revisits the well-known Hong-Ou-Mandel experiment [4].

[1] Near optimal single photon sources in the solid state, N. Somaschi, *et al*. Nature Photonics, doi:10.1038/nphoton.2016.23 (2016)
[2] High-performance semiconductor quantum-dot single-photon sources, P Senellart, G Solomon, A White, Nature nanotechnology 12 (11), (2017)
[3] Boson sampling with single-photon fock states from a bright solid-state source, JC Loredo, *et al.,* Physical review letters 118 (13), 130503 (2017)
[4] Interfacing scalable photonic platforms: solid-state based multi-photon interference in a reconfigurable glass chip, C Antón, *et al*., arXiv:1905.00936
[5] Generation of non-classical light in a photon-number superposition, J. C. Loredo, C. Anton, *et. al*, arXiv:1810.05170

Spectral gap in PEPS

David Perez Garcia, University of Valencia

Abstract: Quantum information theory and the theory of quantum many body systems are inextricably connected. An important part of this connection is mediated through the so called Projected Entangled Pair States (PEPS), variational families of states which mimic the entanglement structure present in ground states and thermal states of quantum many body systems Each PEPS comes together with an associated “parent” Hamiltonian. Proving whether this Hamiltonian is gapped or gapless remains an important open problem. In this talk I will review some recent progress in this problem. (joint work with M. Kastoryano, A. Lucia and A. Pérez.)

Quantum optics and simulation with topological photons

Alejandro González Tudela

Recent experimental advances in nanophotonics [1], circuit QED [2] and atomic physics [3] allow one to engineer systems where atoms (or other quantum emitters) couple to photonic environments with structued energy dispersions. In parallel, an steady state progress is being made to design photons with topological properties in several experimental platforms including dielectric photonic crystals, cavities, or circuit QED, among others [4].

In this talk, we will discuss two recent works [5-6] where we explore the emergent quantum dynamics and interactions appearing when quantum emitters are coupled to topological photonic lattices such as a topological 1D waveguide [5] and a 3D photonic Weyl environment [6]. We will pay particular attention to the possibility of obtaining robust coherent quantum emitter interactions which can be harnessed for quantum simulation of many-body spin Hamiltonians.

[1] Nature 508, 241–244 (2014), Nature Communications 5, 3808 (2014), Rev. Mod. Phys. 87, 347 (2015)

[2] Nature Physics 13 (1), 48-52 (2017)

[3] Phys. Rev Lett. 101 (26), 260404 (2010),Nature Physics 8, 267–276 (2012), arXiv:1712.07791

[4] Rev. Mod. Phys. 91, 015006 (2019)

[5] arXiv:1811.04390

[6] arXiv:1903.07513

Quantum algorithm enhanced quantum sensing

J. Wrachtrup, 3rd Institute of Physics and Centre for Applied Quantum Technologies, University of Stuttgart, Stuttgart, Germany

The development of quantum algorithms is mostly geared towards quantum computing and communication. Little use has been made so far in quantum sensing. While multiparticle entanglement is intensely discussed in sensing, their stabilization against decoherence, by e.g. quantum error correction [1] or dedicated decoupling gates [2] has not been explored. For certain systems, like spin defects in wide band gap semiconductors, which are utilized for nanoscale quantum sensing the use of such algorithms proves to be ideal. In my talk I will explain how to use dedicated quantum control sequences and algorithms, like e.g. the quantum Fourier transformation, to enhance the performance of those sensors and demonstrate applications.

[1] Waldherr et al. Nature 506 (2014) 204ff.

[2] Pfender et al. Nature Communications, Volume 10, Article number: 594 (2019)

Towards implementation security of quantum cryptography

Marcos Curty, University of Vigo

Abstract: Quantum key distribution (QKD) is certainly the most mature application of the future global quantum internet. In theory, it offers information-theoretically secure communications based on the laws of quantum physics. In practice, however, current security proofs of QKD rely on assumptions which are not fulfilled by the real setups, and thus the security of QKD implementations is seriously threatened by quantum hacking. Such assumptions are, for instance, that QKD devices are located in protected labs which prevent any unwanted information to be leaked to the channel, that the legitimate users of the system have a precise mathematical description of the behaviour of their apparatuses and this cannot be modified by the eavesdropper, or that all quantum devices and classical post-processing units are honest and function as prescribed by the protocol. Here, we present recent results that significantly relax these unrealistic and hardly feasible assumptions to achieve high performance QKD with enhanced implementation security.

Even nanoparticles get the entanglement

Prof. Gabriel Molina-Terriza
Ikerbasque Research Professor
Materials Physics Center, Donostia/San Sebastian

With technological advances allowing the fabrication of smaller and smaller components for electronic and optical processing it is important that we understand and embrace the possibilities of combining the use of quantum technologies in the nanosciences. In this talk I will present three recent results of my research group which showcase the possibilities of applying the concepts of Quantum Optics and Quantum Information in Nanophotonics, with particular emphasis in sensing and metrology applications. In particular I will show our recent efforts in using quantum metrology to perform measurements of the optical rotatory dispersion of chiral molecules, how photonic quantum states can be engineered to interact with structures smaller than the wavelength of light and to control the state of levitated nanoparticles.

Single-Shot Quantum Statistical Inference: Change-point and anomaly detection & generalized swap-test

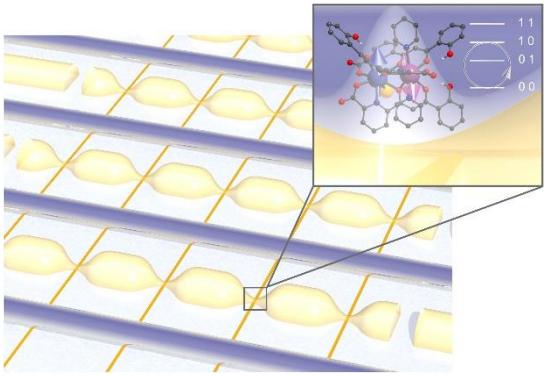
John Casalmiglia, University of Barcelona

Abstract: We overview three statistical inference class of problems that go beyond standard inference problems using repeated experiments to infer properties of the observed systems. The first class is a quantum extension of change-point detection, that aims at identifying the moment when a sequence of observed data changes its underlying probability distribution. We present a quantum instance of this problem where a source emits quantum particles in a default state, until a point where a mutation occurs that causes the source to produce a different state. The problem is then to find out where the change occurred. The second class is quantum anomaly detection where now the change occurs in a single qubit of the string whose position is unknown. In anomaly detection we also consider the extension from sources to general quantum channels, i.e. we study the problem of identifying the position of a malfunctioning device in a sequence of n devices that perform a default fixed operation. Finally, we will discuss the problem of estimating the overlap between two unknown states, given several copies of each of them. We provide an optimal measurement strategy that outperforms the so-called swap-test routinely used for this task.

Scaling up quantum computing with magnetic molecules

Fernando Luis

Instituto de Ciencia de Materiales de Aragón, CSIC-Universidad de Zaragoza, Zaragoza (Spain)



The development of large-scale quantum computing and simulation calls for the integration of a vast number of qubits in a device. A natural option to address this scaling challenge is to use microscopic qubits in a hybrid approach. In this talk, I discuss the application to this field of artificial magnetic molecules. A molecule represents the smallest "nano-object" that, while truly microscopic, remains "tuneable": its relevant properties can be set, with exquisite precision and reproducibility, by chemical methods. In the past few years, it has been shown that simple molecules can perform as spin qubits with sufficiently long coherence times. Besides, they provide model systems to explore fundamental aspects related with, e.g. the energy cost of (quantum) computation. Their design flexibility can also be used as an extra tool for scaling up computational resources: realizations of two- and three-qubit gates have been achieved in molecules with multiple inequivalent spin centers and/or profiting from the internal (nuclear or electronic) spin degrees of freedom of these centers. Even more challenging is how to create a scalable architecture for quantum computation and simulation, as it necessarily implies "wiring-up" many of such molecular units. A promising scheme is based on circuit QED, that is, on linking molecular spins via microwave photons trapped in superconducting on-chip resonators. The technical challenges, limitations and future potential of this scheme will be discussed.

CONTRIBUTED TALKS

Long-lived nuclear spins in rare-earth doped Y_2O_3 nanoparticles

D. Serrano[1,*], J. Karlsson[1], S. Liu[1], A. Fossati[1], A. Ferrier[1,2], A. Tallaire[1], P. Goldner[1]
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[2] Faculté des Sciences et Ingénierie, Sorbonne Université, 75005, Paris, France
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Nanoscale systems possessing long-lived spins and the ability to coherently couple to light are highly demanded for quantum devices implementations. Several approaches, like NV centers in diamond, semiconductor quantum dots are intensively investigated in the field, where an outstanding challenge is to preserve properties, and especially optical and spin coherence lifetimes, at the nanoscale. Here, we investigate the spin coherence properties of rare-earth doped nanoparticles using all-optical spectroscopic methods. We measure spins echoes and demonstrate spin coherence lifetimes up to 8 ms by applying dynamical decoupling, a record value for optically controlled spins in nanomaterials. Furthermore, we observe high fidelity between excitation and echo phases [1]. Rare-earth doped nanoparticles are thus promising candidates for nanoscale quantum memories and quantum sensors.

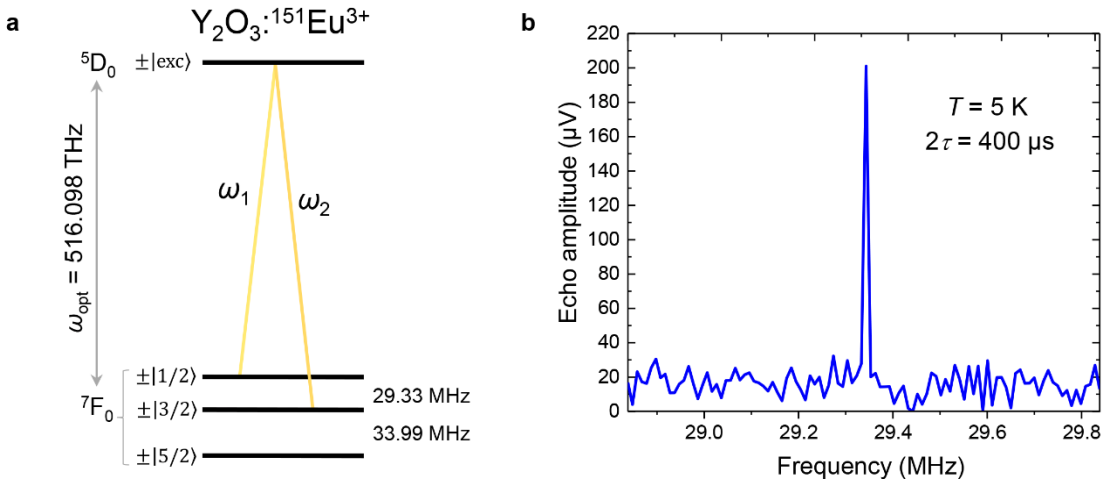

Figure 1: a $^{151}Eu^{3+}$ ground-state hyperfine structure in Y_2O_3. Two color laser pulses (at ω_1 and ω_2 frequencies) resonant with the $^7F_0 \rightarrow {}^5D_0$ transition at 580.883 nm create coherent states between the ±1/2 and ±3/2 nuclear spin levels. **b** Fast Fourier transform of the heterodyne signal revealing the spin echo at 29.34 MHz.

References

[1] D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, P. Goldner, Nature Communications 9 (1), 2127 (2018)

Acknowledgement

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Low-cost error mitigation by symmetry verification

X. Bonet-Monroig [1,2], R. Sagastizabal [2,3], T.E. O'Brien [1] and L. DiCarlo [2,3]

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[2] QuTech, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands
[3] Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

While the number of qubits and performance rates is expected to improve in the upcoming generations of quantum hardware it seems unlikely that they will meet the requirements of quantum error correction schemes. However noisy intermediate-scale quantum (NISQ) devices are thought to be sufficient to show unambiguous quantum advantage by combining algorithms with low experimental requirements such as the variational quantum eigensolvers (VQE) and error mitigation strategies. In this work we investigate the performance of error mitigation via measurement of conserved quantities. We develop two protocols to measure conserved symmetries during the bulk of an experiment, and develop a third, zero-cost, post-processing protocol which is equivalent to a variant of quantum subspace expansion. Additionally, we present methods for inserting global and local symmetries into quantum algorithms, and for adjusting natural symmetries of the problem to boost the mitigation of errors produced by different noise channels. A (classical) full-density-matrix simulator is used to demonstrate these techniques for solving the ground-state dissociation curve of the hydrogen molecule in two- and four-qubits through the VQE algorithm [1]. We experimentally implement our zero-cost error mitigation protocol in two qubits of a circuit QED processor for the same problem [2]. The mitigated result shows up to an order of magnitude improvement in the energy error and state infidelity. We develop an error model for our classical simulator using experimentally measured device parameters that shows good agreement with the experimental data. Finally, we dissect the contributions to the final error from calibrated noise sources by increasing the complexity of the error model in our simulator. Our results demonstrate that symmetry verification shifts the dominant source of error from qubit relaxation and residual excitations to optimization uncertainty and pure dephasing, which is in agreement with our theoretical predictions [1].

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[1] X. Bonet-Monroig, R. Sagastizabal, M. Singh, and T. E. O'Brien, Phys. Rev. A **98**, 062339 (2018).
[2] R. Sagastizabal, X. Bonet-Monroig, M. Singh, M. A. Rol, C. C. Bultink, X. Fu, C. H. Price, V. P. Ostroukh, N. Muthusubramanian, A. Bruno, M. Beekman, N. Haider, T. E. O'Brien, and L. DiCarlo, arXiv:1902.11258 (2019).

Title:
Finite correlation length scaling with infinite projected entangled pair states

Abstract:
I will describe the interplay of criticality and tensor networks in the context of quantum many-body systems. Quantum many-body systems in the strongly correlated regime still defy solution in general, especially close to a critical point of a quantum phase transition. Tensor networks provide a viable numerical technique to address those scenarios, by expressing the state of the system as a contraction of small elementary tensors that are
variationally optimized in order to target the desired states.

I will present numerical results suggesting a fundamental theoretical discovery, the best numerical approximation of a (Lorentz-invariant) critical ground state with an infinite matrix product state (1D) and and infinite Projected Entangled Pair State (2D) is always finitely correlated. This discovery allows us to set up a systematic approach, called finite correlation length scaling, to unveil the universal behavior of a system at a quantum phase transition. We demonstrate the power of this approach by applying it to a model of interacting spinless fermions on a
honeycomb lattice where we find agreement of the critical exponents with previous state-of-the-art QMC results. I also propose an alternative powerful scaling approach to extract the critical coupling without the a priori knowledge of the critical exponents.

These results have important practical applications in diverse fields. In condensed matter physics, for example, quantum critical phenomena lie at the heart of our understanding of exotic emergent behavior in heavy fermion compounds and high-temperature superconductors. The application of tensor networks to high-energy physics is still in its infancy, but our results are key in order to understand how to construct the continuum limit of a lattice gauge theory described by tensor networks.
References
- P Corboz, P Czarnik, G Kapteijns, L Tagliacozzo - arXiv preprint arXiv:1803.08445

Predicting the robust features of the out-of-equilibrium evolution of many-body quantum systems

Jacopo Surace, University of Strathclyde

The fact that the computational cost of simulating a many-body quantum system on a computer increases with the amount of entanglement has been considered as the major bottleneck for simulating its out-of-equilibrium dynamics. Some aspects of the dynamics are, nevertheless, robust under appropriately devised approximations. Here we present a possible algorithm that allows to systematically approximate the equilibration value of local operators after a quantum quench. At the core of our proposal there is the idea to transform entanglement between distant parts of the system into mixture, and at the same time preserving those conserved quantities that can be expressed as a sum of local densities. We benchmark the resulting algorithm by studying quenches of quadratic fermionic Hamiltonians.

Bounding correlations in quantum causal networks

Alejandro Pozas-Kerstjens, Elie Wolfe, Miguel Navascues, Antonio Acin

Causality is a seminal concept in science: any research discipline, from sociology and medicine to physics and chemistry, aims at understanding the causes that could explain the correlations observed among some measured variables. One of the consequences of Bell's theorem is that quantum causes can reproduce some correlations for which an analogue classical explanation is impossible. Furthermore, as demonstrated by Popescu and Rohrlich, it is known that there also exist correlations between variables that cannot be reproduced even by quantum causes.

The development of the Navascués-Pironio-Acín (NPA) hierarchy was a cornerstone of quantum causality that provided numerically-efficient methods to determine whether a given correlation could be generated through performing measurements on quantum systems. Its development made possible the rise of the device-independent paradigm, where systems are considered as black boxes only characterized by the probabilities of obtaining outcomes given some inputs. As such, the NPA hierarchy has been applied in many scenarios, from characterizing the boundaries of the set of quantum correlations, to generating random numbers in a certifiable way or putting bounds to the minimal Hilbert space dimension needed for achieving a correlation.

While incredibly successful, the NPA hierarchy is designed for networks where all variables are related to each other by a common quantum cause, and it cannot accommodate the restrictions of more complex causal structures. Even for simple cases as the scenario underlying entanglement swapping, where two independent quantum hidden variables correlate each of two extreme variables with the same central one, there is a lack of tools to analyze the quantum correlations that can be generated.

In this talk we address such issue presenting two independent methods, quantum inflation and scalar extension, that allow to falsify whether a given quantum causal model can explain some correlations. On one hand, quantum inflation generalizes the inflation technique for classical causal inference and can be used for analyzing quantum correlations in arbitrary causal networks. On the other hand, the scalar extension modifies the NPA hierarchy to allow imposing relaxations of factorization constraints in semidefinite programs, so one can study the set of quantum correlations in networks with causally-independent nodes, such as that underlying entanglement swapping. While being applicable to a subset of the networks where quantum inflation can be applied, scalar extension needs of much less computational resources to identify supra-quantum network correlations. We show examples of use of both methods, and in the case of scalar extension, we report on the phenomenon of measurement non-locality activation, by which measurement devices that are not able to certify nonlocality in a bipartite scenario can be used for certifying nonclassical correlations when placed in tripartite causal networks.

Given the success the NPA hierarchy achieved in bipartite quantum causality, we expect our results to find applications in many fields: from the characterization of correlations in complex quantum networks such as the sought-after quantum internet, to the study of quantum effects in thermodynamic and biological processes.

Refuting observer-independence in quantum theory

Massimiliano Proietti,[1] **Alexander Pickston,**[1] **Francesco Graffitti,**[1] **Peter Barrow,**[1]
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2. Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France.
3. Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria.

When Eugene Wigner conceived his *Gedankenexperiment* in 1961 [1], he argued that in quantum theory two observers, Wigner and his friend, can experience two fundamentally different descriptions of the reality. This called into question whether quantum mechanics is compatible with an observer-independent framework, where observations are objective as suggested by our classical vision of Nature. Yet, only six decades later, this question has been rigorously tackled independently by Brukner [2] and Frauchiger and Renner [3]. They exploit an extended Wigner's friend scenario, which now involves two entangled Wigner and friends leading at two different no-go theorems, where however similarities could be individuated. Here, we demonstrate an extended Wigner's friend scenario based on [2] in a high quality 6-photon experiment realised in a state-of-the-art photonic platform, Fig. 1.

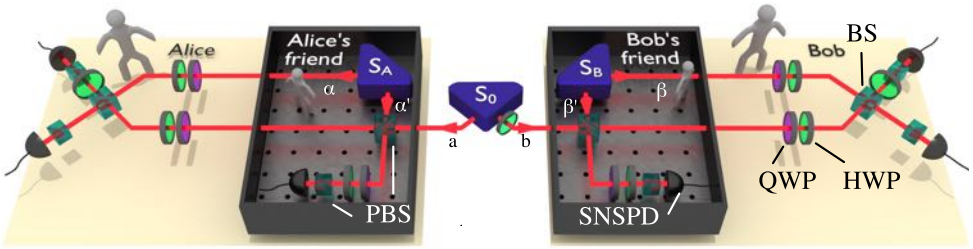

Figure 1: Pairs of entangled photons from the source S_0, in modes a and b, are distributed to Alice and Bob's friends respectively, who locally measure their incoming photon in the h,v basis using entangled sources S_A, S_B and type-I fusion gates. The latter exploit nonclassical interference on a polarising beam splitter (PBS), between photons in mode α' and a for Alice's friend, β' and b for Bob's friend. A detection with superconducting nanowire single photon detectors (SNSPD), heralds the success of the measurement. The Alice and Bob's friends' measurement outcome is recorded in the polarization of photons in modes α and β respectively. Alice (Bob) then either infer the fact observed by their respective friend or performs a Bell-state measurement to establish her (his) own fact.

We employ as a resource of entanglement three Sagnac interferometers embedded with high purity and brightness probabilistic single-photon sources [4]. We prepare Bell-states with typical fidelity $F = 99.62^{+0.01}_{-0.04}\%$ and entanglement as measured by the concurrence $C = 99.38^{+0.02}_{-0.10}\%$. Two type-I fusion gates applied to the three initial 2-qubit states lead to the preparation of a 6-photon maximally entangled state, generating up to 1 six photon coincidence per second. We therefore measure correlations of observables corresponding to facts established by Alice, Bob and their friends, tested by a CHSH-type inequality for observer-independent facts as described in [2]. We observe for such inequality the experimental value of 2.416 ± 0.075. The violation of the inequality implies that at least one of these four assumptions must fail [2]: free choice, locality, universal quantum mechanics, and observer-independent facts. Since abandoning locality and free choice might not resolve the contradiction, one way out would be to give up universality implying the existence of a preferred frame of reference from which quantum mechanics should be applied, such as the global wavefunction in the many worlds interpretation or Bohmian mechanics. Another option is to give up objective reality, either by considering facts only relative to observers, or by adopting an interpretation such as Quantum Bayesianism, where the wavefunction represents an observer's subjective predictions. Alternatively, one could invoke superluminal or even retro-causal influences. However, every choice must inevitably sacrifice cherished classical principles.

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Hot, dense atomic media for measurement-based quantum optical technologies

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We study non-local entanglement and macroscopic singlet state generation in a hot, strongly-interacting atomic system by using quantum non-demolition (QND) measurement, and particularly, the Bayesian estimation technique of Kalman filtering (KF) [1] to recover the spin information. By comparing the total spin variance against spin squeezing inequalities [2], we observe 1.9 dB spin squeezing, and at least 1.5×10^{13} atoms have entered singlet state with entanglement bonds extending thousands of times the nearest-neighbor distance. The results show that the hot, strongly-interacting media, now in use for extreme atomic sensing, together with QND and KF techniques can operate beyond the standard quantum limit (SQL).

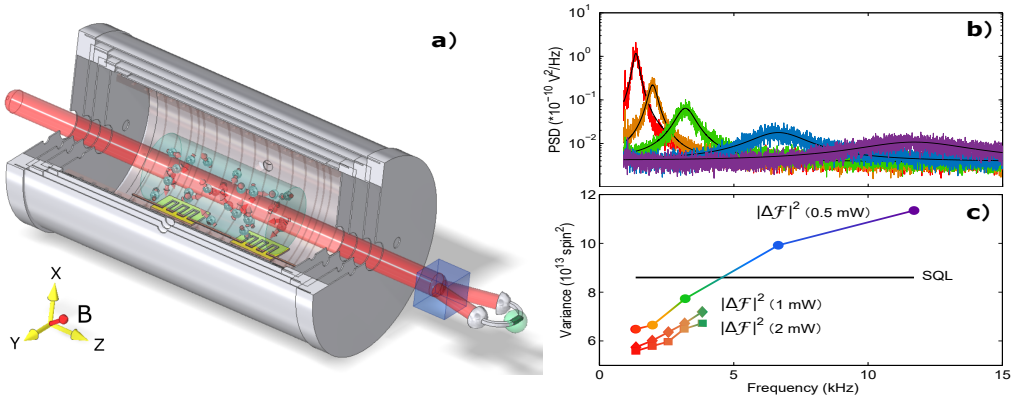

Figure 1: Experimental Principle. **a)** Experimental setup. **b)** Spin noise spectra with different bias field strengths. **c)** Spin variance $|\Delta\mathcal{F}|^2$ versus Larmor frequency corresponding to the spectra in b). Black solid-line shows the standard quantum limit (SQL). Round, diamonds and squares symbols show $|\Delta\mathcal{F}|^2$ measured with 0.5 mW, 1 mW and 2 mW probe light, respectively.

We work with a vapor of ^{87}Rb contained in a glass cell with buffer gas to slow diffusion, and housed in magnetic shielding and field coils to control the magnetic environment, see Fig. 1 **a)**. The density is maintained at $n_{Rb} = 3.6 \times 10^{14}$ atoms/cm^3, and the magnetic field, applied along the $[1, 1, 1]$ direction, is used to control the Larmor precession frequency $\omega_L/2\pi$. At low ω_L, the vapor enters the SERF regime, characterized by a large increase in spin coherence time as shown in Fig. 1 **b)** with spin noise spectroscopy [3]. The KF provides both a best estimate and a covariance matrix for the state variable, which gives an upper bound on the variances of the post-measurement state. In particular, the total variation can be compared against spin squeezing inequalities to detect and quantify entanglement. Fig. 1 **c)** shows the total variance including a transition to squeezed/entangled states as the system enters the SERF regime.

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Plug-and-play continuous variable quantum key distribution system with a true local oscillator

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Continuous variables quantum key distribution (CV-QKD) based on coherent states enables two parties to share a secret key by using weak attenuated pulses of light and coherent detection. CV-QKD can be implemented with low-cost and mature components developed for telecommunications, making it a promising technology for its integration into current network infrastructure. Typically, the implementation of CV-QKD with true local oscillator requires two frequency-locked narrow-linewidth laser sources, which increases significantly the overall cost and the technological overhead of the system. Recently, a plug and play CV-QKD has been proposed where a single laser is split and sent to both parties to serve as a source to prepare quantum states of light and also as the local oscillator. However, due to the presence of strong light at the same frequency and in the same fiber as the quantum states, the excess noise of the system increased because of the unavoidable Rayleigh scattering. Here we propose to overcome this problem by using two fiber links instead of one to transmit the light to the other party. In this way, we demonstrate a plug-and-play CV-QKD prototype with true local oscillator that carries out the four quadrature amplitude modulation (4-QAM) protocol. Figure 1a shows a schematic of the system. We note that traditional fiber communication links possess several fiber strands that can be used simultaneously, therefore our system could be implemented in current network infrastructure.

Preliminary results show that the present prototype enables accurate measurement of the quadrature values (Figure 1b) and can operate at a distance of 10 km with a secret key rate of approximately 1 Mb/s (Figure 1c). Future directions include the incorporation of classical light into the two fibers links, which would facilitate the implementation of our prototype in real network scenarios

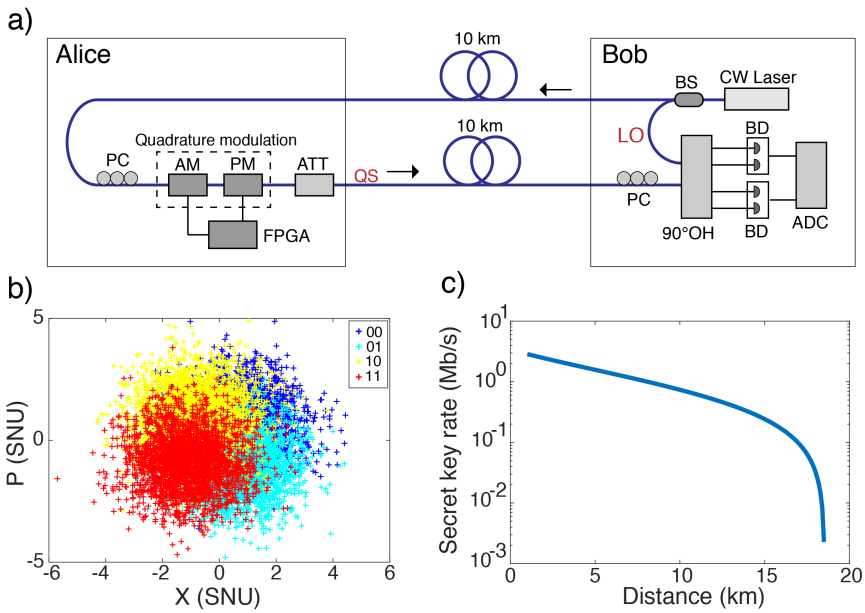

Figure 1. a) Simplified experimental setup. PC: Polarization controller, AM: Amplitude modulator. PM: Phase modulator. ATT: Attenuator. 90°OH: 90° Optical Hybrid. BD: Balanced detector. ADC: Analog-to-digital converter. QS: Quantum signal. LO: Local oscillator B) Quadrature's values measured by Bob. SNU: Shot noise units. c) Secret key rate as a function of the distance.

Entanglement Between a Photonic Time-Bin Qubit and a Collective Atomic Spin Excitation

Entangled states between light and matter play a central role for fundamental tests in quantum physics and are an important resource for emerging quantum technologies [1]. Their main key feature is that they combine the advantages of "flying" photonic states (that provide long distance transmission) with the ones of "stationary" atomic states (that enable quantum state storage, synchronization and processing). For long distance transmission of the photonic states, using the time-bin qubit encoding is favourable, being robust against decoherence in optical fibers. In this work, we demonstrated direct generation of entanglement between a photonic time-bin qubit and a collective atomic spin excitation (spin-wave) using an ensemble of laser-cooled atoms [2].

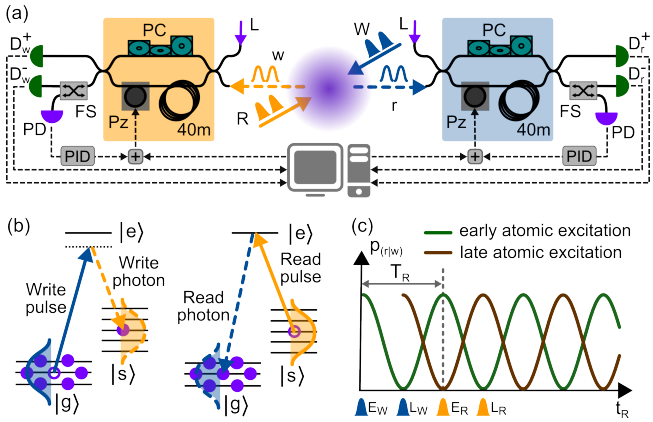

Fig. 1 (a) Experimental setup (b) Atomic level scheme involved in the entanglement generation. (c) Laser pulse times with respect to the atomic excitation rephasing times.

The basic concept of the experiment is as follows (cf. Fig.1). An off-resonant doubly-peaked write laser pulse (W) generates an excitation in our atomic cloud that is entangled with a Raman scattered write photon (w) in the time-bin degree of freedom. This entangled state can be written as $|\Psi_{\mathrm{wa}}\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{E_wE_a}\rangle + e^{i\phi}\,|\mathrm{L_wL_a}\rangle\right)$, where $\left|\mathrm{E_{w(a)}}\right\rangle$ and $\left|\mathrm{L_{w(a)}}\right\rangle$ denote a write photon (atomic excitation) generated in the early and late bin, respectively. In order to generate this entangled state, the atomic excitations generated at the two time bins need to form an orthogonal qubit basis (i.e. they need to be totally distinguishable). This is achieved applying an homogeneous magnetic field that leads to a Zeeman splitting of the atomic energy levels and induces a dephasing and rephasing of the excitation at well defined periods ($\mathrm{T_R}$) after its creation (see Fig.1b and 1c).

To assess the matter qubit, this is converted into a read photon time-bin qubit (r) using a resonant read laser pulse (R), and the two entangled photons are analysed. This analysis is done with Mach-Zehnder interferometers and single photon detectors $\mathrm{D^{+(-)}_{w(r)}}$, which allow projective measurements in any basis on the equator of the Bloch sphere. The long temporal separation between the early (E) and late (L) photonic time-bins, requires interferometers with long length difference between the short and long arms ($40\,\mathrm{m}$). This large imbalance makes it challenging to maintain a stable phase delay during the experiment. In order to achieve that condition, a short section of the long fiber arm is rolled around a piezo-electric ceramic cylinder (Pz) for active feedback using lock laser light (L).

To prove the entanglement we obtain a CHSH Bell parameter of $S = 2.18 \pm 0.09$, violating the Bell inequality by 2 standard deviations. We also obtained similar results using human random numbers to decide the measurement settings, contributing to test the freedom-of-choice loophole in Bell tests [3].

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Quantum devices outperforming classical computers

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This talk submission comprises two works, [1] arXiv:1703.00466 and [2] arXiv:1706.03786.

A near-term goal in quantum computation and simulation is to realize a quantum device showing a computational advantage (or "quantum computational supremacy"). The goal here is to perform a quantum experiment whose outcome cannot be efficiently predicted on a classical computer. A hope of this program is that performing such an experiment may be simpler than building a fault-tolerant universal quantum computer. Candidate quantum devices for this task include boson samplers [3] and Google-AI's random quantum circuits [4].

In this talk, we will review the current approaches towards rigorously demonstrating superior quantum computational power, as well as associated challenges concerning scalability, verifiability and complexity theoretic soundness. We will then introduce a new proposal [1-2] based on short-time evolutions of 2D Ising models [1-2]. Our proposal has the benign features of (1) being hard to simulate classically (assuming plausible complexity theoretic conjectures) while (2) being reasonably close to cold-atomic quantum implementations, and (3) admitting an efficient simple quantum verification protocol. The conjectures involved are natural and analogous to those underpinning the celebrated boson sampling proposal. This provides a new alternative path towards demonstrating a reliable quantum advantages.

Our work also provides high theoretical evidence that reliable and computationally-superior analogue quantum simulators [5] can be realized. This complements available empirical evidence that state-of-the-art classical tensor network algorithms cannot simulate recent cold-atomic quantum simulation experiments [6,7]. The latter works do not provide a strong demonstration of superior quantum computational power, since, taking the role of devil's advocate, better classical simulation algorithms for these experiment could still be found. Our work, on the other hand, provides a strong complexity-theoretic demonstration that analogue quantum simulators can indeed outperforming classical supercomputers.

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Classical Ising models are among the most paradigmatic and widely studied models in statistical physics. They are capable of describing an immense variety of interesting physics, ranging from ferromagnetic to frustrated and glassy phases. Moreover, Ising models can also be used to encode optimization problems that have relevant applicaitons in fields as diverse as risk assessment in finance, logistics and machine learning.
An ubiquitous question for such optimization problems is to determine the ground-state energy and configuration of these models. The generality and exponentially growing configuration spaces of such models, however, precludes the existence of any efficient general purpose algorithm to obtain the ground state.
It is hence no surprise that a wealth of approximate but more scalable classical techniques for the energy minimization in such models has been developed.

Recently, novel approaches that leverage the power of near-term quantum devices such as quantum annealers, variational quantum eigensolvers, or networks of degenerate optical parametric oscillators, are proposed for performing such tasks.
The most scalable of the classical approaches based on simulated annealing or variational ansatz classes, as well as the mentioned quantum mechanical methods, however, all have one thing in common: they only yield upper bounds on the ground state energy.
A comparison of such upper bounds can provide a ranking of the methods' performance for benchmark tasks. Nevertheless, it cannot guarantee that the obtained upper bounds are actually close to the true ground state energy and, even if this is the case, there is no guarantee that the final spin configuration is anywhere near that of the true ground state, or just corresponds to a far away local minimum.
It is thus a problem of great importance to develop schemes that provide lower bounds to the ground state energy, against which the results of such widely used upper-bound techniques can be compared.

In this talk, I will address this issue and consider the use of relaxations to polynomial optimisation problems using semi-definite programming (SDP) to derive lower bounds to the ground-state energy of classical spin systems. I will also show how the SDP solution can also be used to extract a guess for a spin configuration. In this way, exploiting the same method yields both a lower bound and an upper bound to the ground state energy with a computational effort that is polynomial in the size of the system.
I will then introduce a novel technique, the so-called chordal-branch-and-bound (CBB), which combines the above-mentioned relaxation with two existing techniques, namely the chordal extension and the branch-and-bound algorithm.
On the one hand, the chordal extension provides a more scalable SDP relaxation to the ground state energies of spin models of interest in physics by consistently exploiting their sparsity pattern. On the other hand, the branch-and-bound allows one to combine the obtained upper and lower bounds in a series converging to the exact solution.

Finally, I will show how the introduced CBB method can be used to verify the solution of quantum annealing devices such as the D-Wave 2000Q machine. Interestingly, the imporved scalability of our method allows one to address problems with the largest system size that can be encoded in current annealing machines.
As I will demonstrate, the CBB method is indeed capable of identifying instances where the solution provided by D-Wave is far from the exact ground state energy, thus proving that the quantum annealer has reached a local minimum.

The talk will be based on the results of arxiv:1808.01275.

Quantum entanglement study of the two-component Bose-Hubbard model

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ABSTRACT

The Bose-Hubbard model is nowadays almost ubiquitous in the interpretation of ultracold atomic gases experiments with optical lattices[1]. It provides the prime ingredient that allows ultracold atomic setups to mimic well-known many-body problems[1,2]. In particular, it makes these systems extremely competitive for building quantum simulators of a wide range of notably difficult physical problems[3,4]. A particularly relevant example is the use of a two-component Bose-Hubbard (TCBH) model as a quantum simulator of spin models[4–6]. As pointed out in those papers different spins, e.g. $1/2$, 1, etc, can be simulated depending on the filling factor of the two species in the chain. In this article we concentrate on a specific configuration of filling one for both species, i.e. equal number of atoms of both species in the chain which maps into a spin-1 system. In this case, the TCBH maps, using perturbation theory, into a Heisenberg model with ferromagnetic interactions[5].
In our work[7] we consider the question: To what extent does the quantum simulator exhibit similar entanglement properties than the simulated Hamiltonian? In particular, we focus on critical regimes where specific entanglement properties universally characterize the phase of the system. The analysis will be performed in the strongly interacting regime, where the interaction strength of both species is equal and much larger than the tunneling rate. We will study the entanglement properties of the system as the interspecies interaction is increased towards the point where all interactions match. In this way, the simulated spin model goes from an anisotropic Heisenberg model into the Heisenberg isotropic one. Analytical results using perturbation theory will be complemented with numerical calculations using DMRG (density matrix renormalization group). In this way we can compare the entanglement present in the TCBH with that of the spin model, paying particular attention to the critical phases which appear in the latter.

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A resource theory of entanglement with a unique multipartite maximally entangled state

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Entanglement is a striking feature of quantum theory with no classical analogue. Although initially studied to address foundational issues, the development of quantum information theory in the last few decades has elevated it to a resource that allows tasks to be implemented which are impossible in classical systems. The resource theory of entanglement aims at providing a rigorous framework to qualify and quantify entanglement and, ultimately, to understand fully its capabilities and limitations within the realm of quantum technologies. However, this theory is much more firmly developed for bipartite systems and a deeper understanding of the complex structure of multipartite entangled states might inspire further protocols in quantum information science and better tools for the study of condensed-matter systems.

The main question a resource theory addresses is to order the set of states and provide means to quantify their nature as a resource. The so-called free operations are crucial to this task. This is a subset of transformations, which the given scenario dictates can be implemented at no cost. Thus, all states that can be prepared with these operations are free states. Conversely, non-free states acquire the status of a resource: granted such states, the limitations of the corresponding scenario might be overcome. Moreover, the concept of free operations allows an order relation to be defined. If a state ρ can be transformed into σ by some free operation, then ρ cannot be less resourceful than σ since any task achievable by σ is also achievable by ρ as the corresponding transformation can be freely implemented. However, the converse is not necessarily true. Furthermore, one can introduce resource quantifiers as functionals that preserve this order.

Entanglement theory is usually formulated as a resource theory in which the free operations are local operations and classical communication (LOCC). This defines a partial order among bipartite pure states that makes it possible to identify a maximally entangled state, which turns out to be the most relevant state in applications. However, the situation changes drastically in the multipartite regime. Not only do there exist inequivalent forms of entanglement forbidding the existence of a unique maximally entangled state, but recent results have shown that LOCC induces a trivial ordering: almost all pure entangled multipartite states are incomparable (i.e. LOCC transformations among them are almost never possible). In order to cope with this problem we consider alternative resource theories in which we relax the class of LOCC to operations that do not create entanglement. In more detail, we consider two possible theories depending on whether resources correspond to multipartite entangled or genuinely multipartite entangled (GME) states and we show that they are both non-trivial: they induce a meaningful partial order since every pure state is deterministically transformable to more weakly entangled pure states. Moreover, we also show that no inequivalent forms of entanglement exist in these theories (i.e. all resource states are interconvertible with non-zero probability). Last but not least, we prove that the resource theory of GME that we formulate here has a unique maximally entangled state, the generalized GHZ state, which can be transformed deterministically to any other state by the allowed free operations.

This contribution is based on arXiv:1807.11395 (accepted in Phys. Rev. Lett.).

Unsupervised classification of quantum data

Gael Sentís, Alex Monràs, Ramon Muñoz-Tapia, John Calsamiglia, and Emili Bagan

Unsupervised learning is a class of machine learning primitives concerned with extracting features from unlabelled data, and it stands as one of the fundamental tools in data mining. Its most representative primitive is unsupervised classification or clustering, where a (large and unsorted) set of data instances are given and promised to be generated from two (or more) distinct but otherwise uncharacterized sources. The task then consists in clustering the given instances into suitable data sets which likely share a common source. We study the analogous problem in a quantum setting: we are given a number N of quantum systems with the promise that each of them is in one of two possible states, and our aim is to determine which systems share a common state without having any knowledge of what the states could possibly be. We find the best single-shot protocol that performs such task with optimal average success probability.

The optimal quantum clustering protocol displays remarkable features. Firstly, regarding performance, we show that the success probability of guessing the correct clustering scales as Ps~O(d/N^2), where d is the local dimension of the quantum systems. When comparing this result with the performance of the analogous classical problem, we find that the local dimension has the opposite effect in the latter: increasing d exponentially suppresses the success probability. Secondly, in spite of the fact that clustering requires measuring the systems, optimal clustering preserves information about the individual states of the systems, in turn enabling further usage once sorted. Finally, we show that our results do not depend strongly on the figure of merit chosen, but stem instead from the structure of the problem.

The fact that there exists a feasible unsupervised quantum clustering protocol opens the door to designing universal quantum devices able to automatically sort unordered quantum data strings. Such devices can easily be envisioned to be part of the design of future quantum communication networks. Our results represent a complete analytical study of the quantum clustering problem under minimal assumptions about a pure state source: one that produces randomly two possible states. There are numerous extensions that immediately stem from our formalism, and that will enhance the usability of quantum clustering devices in real-world quantum technological applications. These include more than two types of states, information retrieval strategies post-clustering, and entanglement-assisted clustering of quantum processes, to name a few.

Using and reusing coherence to realize quantum processes

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Coherent superposition is a key feature of quantum mechanics that underlies the advantage of quantum technologies over their classical counterparts. Recently, coherence has been recast as a resource theory in an attempt to identify and quantify it in an operationally well-defined manner. Here we study how the coherence present in a state can be used to implement a quantum channel via incoherent operations and, in turn, to assess its degree of coherence. We introduce the robustness of coherence of a quantum channel—which reduces to the homonymous measure for states when computed on constant-output channels—and prove that: i) it quantifies the minimal rank of a maximally coherent state required to implement the channel; ii) its logarithm quantifies the amortized cost of implementing the channel provided some coherence is recovered at the output; iii) its logarithm also quantifies the zero-error asymptotic cost of implementation of many independent copies of a channel. We also consider the generalized problem of imperfect implementation with arbitrary resource states. Using the robustness of coherence, we find that in general a quantum channel can be implemented without employing a maximally coherent resource state. In fact, we prove that *every* pure coherent state in dimension larger than 2, however weakly so, turns out to be a valuable resource to implement *some* coherent unitary channel. We illustrate our findings for the case of single-qubit unitary channels. The published paper was published in Quantum Journal and is available here.

Limits on spectral resolution measurements by quantum probes [1]

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The limits of frequency resolution in nano-NMR experiments have been discussed extensively in recent years. It is believed that there is a crucial difference between the ability to resolve a few frequencies and the precision of estimating a single one. Whereas the efficiency of single frequency estimation gradually increases with the square root of the number of measurements, the ability to resolve two frequencies is limited by the specific timescale of the signal and cannot be compensated for by extra measurements. Here we show theoretically and demonstrate experimentally that the relationship between these quantities is more subtle and both are only limited by the Cramér-Rao bound of a single frequency estimation.

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The TRAPSENSOR facility: precision experiments in Penning traps with a single laser-cooled $^{40}Ca^{+}$ ion as a detector

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In recent years, a novel detection technique with a prime application on single-ion Penning trap mass spectrometry [1] is under development at the University of Granada. Within this approach, a single laser-cooled $^{40}Ca^{+}$ ion is employed as a high-sensitive sensor of electric signals with prospects to detect the one generated by another ion stored in an adjacent Penning trap, after coupling of the ions is achieved through the current induced on the trap electrodes. The completion of this experimental concept may prove beneficial in high-precision measurements on superheavy elements produced in Radioactive Ion Beam facilities (see e.g. [2]). Furthermore, the realization of the experiment in the quantum-limited regime may open new possibilities in the field of quantum metrology with trapped ions.

In this contribution, the TRAPSENSOR facility will be presented, with special focus on the ongoing work with a double-microtrap setup [3] to investigate the coupling between ions in the radiofrequency regime before its implementation in the open-ring 7 T Penning trap, where the infrastructure developed for fluorescence detection of laser-cooled $^{40}Ca^{+}$ ions has been built and Doppler cooling of ion clouds has been observed for the first time in such high magnetic field [4].

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POSTERS

Non-Markov Enhancement of Maximum Power for Quantum Thermal Machines

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In this work we study how the non-Markovian character of the dynamics can affect the thermodynamic performance of a quantum thermal engine, by analysing the maximum power output of Carnot and Otto cycles departing from the quasi-static and infinite-time-thermalization regime respectively. In our model, non-Markovianity is introduced by allowing some degrees of freedom of the reservoirs to be taken into account explicitly and share correlations with the engine by Hamiltonian coupling. It is found that the non-Markovian effects can fasten the control and improve the power output.

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Entanglement through qubit motion and the dynamical Casimir effect.

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We explore the acceleration radiation and the dynamical Casimir effect (DCE) in the field of superconducting quantum technologies, analyzing the generation of entanglement between two qubits by means of the DCE in several states of motion. We show that the correlated absorption and emission of photons is crucial for entanglement, which in some cases can be linked to the notion of simultaneity in special relativity.

Quantum repeaters with optimal encoding from absolutely maximally entangled states

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(Dated: March 7, 2019)

We extend the relation between absolutely maximally entangled (AME) states and quantum maximum distance separable (QMDS) codes by giving a construction to generate whole families of QMDS codes from their parent AME states. We then relate this to optimal codes for quantum repeaters, and establish that AME states provide an overarching framework for QMDS codes that can be used in quantum repeaters.

EXTENDED ABSTRACT

One-way quantum repeaters are networks of nodes that use quantum error correction codes to protect the information that is being transmitted and make a round of error correction at each node, without relying on heralded entanglement generation. There have been several proposals for the codes that should be used: the simple and largely redundant quantum parity codes were studied at the beginning [1], whereas more sophisticated codes like quantum polynomial codes [2] and quantum Reed-Solomon codes [3] have been proposed more recently. We argue that, at least from a theoretical point of view, quantum maximum distance separable (QMDS) codes, those that have the maximum possible distance given the length of the code and the length of the message, should be optimal for quantum repeaters, and propose a way to design them from absolutely maximally entangled states (AMEs).

AMEs are good candidates to maximize entanglement in a given Hilbert space and to be useful resources for concrete implementations. They are characterized by having a completely mixed state in all its balanced bipartitions, and therefore the maximum possible average entropy. However, they do not exist in all possible Hilbert spaces. For qubits, they only exist for 2, 3, 5 and 6 parties, whereas Refs. [5–7] have shown that AMEs do not exist for 4, 7 and more than 8 parties, respectively. A thorough table on the existence of AMEs for many different Hilbert spaces can be found in Ref. [8].

AMEs are connected to both classical and quantum error correction codes [9–11]. In particular, AMEs were shown to be equivalent to some special QMDS codes in Ref. [7]. However those codes are not useful by themselves, and it remained to be seen whether AME states can be used to develop useful codes of arbitrary size. This work argues that the answer is positive, showing a construction to obtain many useful QMDS codes from AME states in their stabilizer form. This means that an AME state may be the resource needed to implement any QMDS code in a practical application. Some applications have already been proposed for AMEs, like parallel teleportation and quantum secret sharing [12]. Exploiting their relation to QMDS codes to use them as resources for one-way quantum repeaters, where we want the maximum possible number of erasure errors to be corrected by our code, could therefore be a new relevant application. This will provide us with a framework within which all efficient quantum error correction techniques, for quantum repeater applications, can be modelled, designed and understood.

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Cold atoms simulator of quantum chemistry

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Computing the electronic structure of molecules is a central challenge in industry, catalysis research or drug design. Despite the enormous success of approximate methods, facing this problem exactly with conventional computers is still a tremendous challenge. This has triggered theoretical and experimental efforts to solve chemistry problems using quantum computers [1], with proof-of-concept results using a few qubits [2] . An appealing alternative to this digital approach is analog quantum simulation, which relies on a highly controllable device the simulator to mimic the system of interest and gain information about the desired solution, and does not require a fully operative computer.

Here we will introduce our recent proposal about how it is possible to also simulate quantum chemistry problems using ultra-cold atoms as a simulator [3]. In this simulator, fermionic atoms hopping in an optical potential play the role of electrons, additional optical potentials provide the nuclear attraction, while a single spin excitation over a Mott insulator mediates the electronic Coulomb repulsion. We analyze the impact of discretization and finite size effects of the lattice, and provide the working conditions required for the precise determination of the electronic energy of simple molecules.

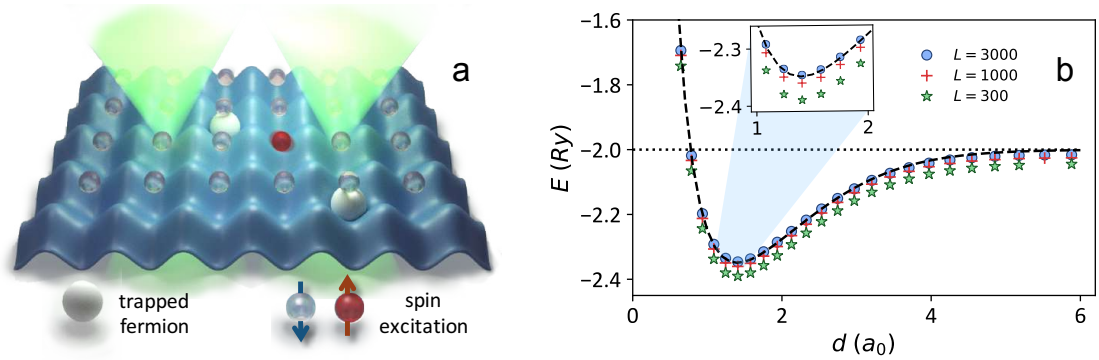

Fig. 1 a Illustration of the simulator for the H_2 molecule. Fermionic atoms (white) play the role of electrons and nuclear attraction is mediated using external lasers (green). A single excitation of a Mott insulator mediates electronic repulsion. **b** Molecular potential associated to an analog simulator in a lattice of 75 sites per side. Under the appropriate choice of parameters, the result agrees with an accurate solution in the nonrelativistic regime (dashed line).

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Quantum walks and lattice gauge theories

It will be shown, in a single-particle framework, that discrete-time quantum walks (DTQWs) provide simple, natural spacetime discretizations of relativistic field theories (the walker typically coincides, in the continuum limit, with a Dirac field), that is: not only (i) are they unitary, but (ii) the evolution operator is also local, i.e., from one instant to the next one, the particle remains within a certain spacetime-lattice 'lightcone' (a spacetime-lattice counterpart to the standard, continuum one). In the discretizations provided by standard lattice gauge theories (LGTs), both properties (i) and (ii) are not straightforward, need to be evaluated, and may not be obtainable.

In a first part will be presented various such DTQWs, which are all connected to their continuum counterpart by a limit procedure in which the space step is kept proportional to the time step. It will be shown that one can describe, in this framework, couplings of the walker to Abelian Yang-Mills gauge fields in one, two, and three dimensions, and also to gravitational fields in one, two, and three dimensions. A 1D model with non-Abelian Yang-Mills coupling will be presented. The models with Yang-Mills couplings have exact lattice gauge invariance. The dynamics of the Yang-Mills gauge fields will be discussed.

In a second part will be presented a DTQW having a continuous-time limit while keeping space discrete (in contrast with the previous models), which coincides with the Hamiltonian formulation of LGTs, i.e., that of Kogut and Susskind, which is extensively used in works on the quantum simulation of LGTs. As any DTQW, this time discretization is unitary and has a local evolution operator, but then, by Meyer's no-go lemmas, it must break translational invariance, that is, the staggered description of chiral symmetry.

All results are in a single-particle framework.

ABSTRACT: The positivity problem in quantum many-body systems

The positivity problem is the difficulty of representing a mixed state with tensor networks. Namely, how is the global positivity of the state translated to the local tensors? There are two natural ways of representing a mixed state by means of tensor networks: the Matrix Product Density Operators (MPDO) and the local purification form. The former is easy to obtain but, on the other hand, the global positivity is invisible at a local level. In the local purification, local positivity is imposed but the description is no longer efficient. The idea is to find an approximate purification such that it has some local certificate of positivity and it is efficient. I will explain this problem in more detail and some results towards this approximate purification form.

Microwave quantum engineering in micro ion traps for applications in quantum technologies

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Among the most promising platforms for future applications in quantum technologies excel trapped ions. Although many of the requirement for building a large-scale quantum computer have been demonstrated in this system [1], scaling of qubit operations to many qubits remains still very challenging. Here we present recent results achieved in our group, in which the operation and characterization of surface-electrode ion traps based on the near-field gradient approach [2] is the central focus. On a first part, ion trapping and microwave control of the hyperfine states on a laser cooled $^{9}Be^{+}$ ion trapped 70 µm above a single-layer trap is presented. In this trap we demonstrate motional-sideband ground state cooling, low motional heating rates and a two-qubit fidelity gate [3] of 98.2 % on a field-independent qubit. On a second part, we present the fabrication, operation and first characterization of a multilayer ion trap with integrated 3D microwave circuitry [4]. This trap features not only a set of conductors to induce single and multi-qubit operations but also generates a low residual field and a high magnetic field gradient at the trap center, as measured by a single $^{9}Be^{+}$ ion [4]. The multilayer fabrication method used for this trap is capable of integrating several thick-metal and planarized thick-dielectric-layers [5] and will allow not only ease of trap signals routing, but also the integration of other key components such as micro-optics, electronic and detection systems into the same trap.

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Zero- and ultra-low field experiments with an optically pumped magnetometer

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Advanced quantum applications are based on the coherent manipulation of individual qubits. The require physical systems that are well isolated against the environment to ensure long coherence times. Quantum states defined by nuclear spin eigenstates can fulfill this requirement due to their weak coupling to the environment. The potential of nuclear spin-based quantum computing has been demonstrated in nuclear magnetic resonance (NMR) experiments as well as in nitrogen-vacancy (NV) centers in diamond.

NMR experiments are usually performed at high magnetic fields with the read-out realized by measuring the magnetic field that generated by the precession of the nuclear spin and their corresponding magnetic moments. Recently, a new type of NMR experiments has awakened increasing attention. Instead of using superconducting magnets for the generation of large magnetic fields, NMR experiments can also be performed in an environment with zero and ultra-low field (ZULF). Here, the nuclear spin states can be read-out by directly measuring the magnetic field with an ultra-sensitive optically pumped magnetometer.

In the ZULF regime the usually dominating Zeeman term is degraded to a perturbation of the full interaction Hamiltonian. The increased prominence of other types of interaction, e.g. J-coupling, allows new ways to implement quantum gates.

On the detector side there is also potential for quantum enhanced atomic magnetometry. Polarization squeezed light could enhance the sensitivity to improve the read-out fidelity. ZULF NMR experiments form a unique combination of two quantum systems, that can give new insights in both quantum metrology, -optics and -information technology.

Simple explanation of quantum correlations

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(Dated: March 13, 2019)

Considerable efforts have been devoted searching the principle that explains why some forms of nonlocality and contextuality are possible in nature and others are forbidden. Here, we show that the assumptions that statistically independent experiments exist and that every behavior that is not forbidden is compulsory, single out the same set of behaviors that quantum theory predicts for any Bell and Kochen-Specker contextuality scenario. As a byproduct, our result explains why the so-called almost quantum correlations are nonphysical.

Preparation of atom-number states by means of Rydberg blockade and electromagnetically-induced transparency.

Daniel Cano Reol.

Preparation of atom-number states by means of Rydberg blockade and electromagnetically-induced transparency

Atom-number states are a valuable resource for atom interferometry and quantum metrology. This theoretical work describes a method for the deterministic generation of atom-number states using the Rydberg blockade in combination with electromagnetically induced transparency. Starting with all atoms in the same ground state, the atomic populations are transferred adiabatically into the desired atom-number state. The proposed method considers the situation in which all atoms are inside the blockade volume. To evaluate the optimal experimental conditions, this work shows numerical simulations using Rydberg-Rydberg potentials for Rubidium atoms.

Quantum digital simulation of three toy models using IBM quantum hardware

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Using the phase estimation algorithm it is possible, in principle, to obtain the eigenstates of a large family of many-body Hamiltonians. Here we present the results of our attempts to implement this algorithm and its iterative version to obtain the eigenvalues of 3 simple model Hamiltonians, using IBM quantum hardware. For that matter, we have considered a two-level system, a two-site Ising model with longitudinal magnetic field, and a two-site Hubbard model at half filling. We have introduced a classical post-processing of results capable of improving the accuracy error bound on the estimated phase while needing one qubit less and being robust to uniform noise. We have explored to which point the unwanted hardware noise compromises the accuracy of the algorithm. In the case of the Hubbard model, for which a Trotterization procedure is required, we study the optimal number of Trotter steps for the first two orders of the decomposition. Our results illustrate the limits of the phase estimation approach for quantum digital simulation in state-of-the-art hardware.

Towards detecting single rare-earth-ions in the solid-state

Chetan Deshmukh

Rare-earth-ions in the solid-state have excellent optical and spin coherence properties at cryogenic temperatures. This makes them a promising candidate for use as a hardware platform to implement various quantum information applications. While great progress has been made towards using ensembles of them for these purposes, the low emission rates of rare-earth-ions has prevented them from reaching the single-ion level. However, there are several advantages to be had by using a single REI, such as high-efficiency spin-photon interfaces as well as the possibility to perform quantum gates by using dipole coupling between two nearby single-ions. Coupling a single REI to a cavity with high-finesse and low mode-volume simultaneously allows for increasing the emission rate as well as increasing the collection efficiency of this emission, both of which are highly desirable. This poster describes our effort towards achieving this goal using erbium doped yttrium oxide nano-crystals coupled to fiber-based micro-cavities.

Molecules & quantum information: recent advances

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Magnetic molecules as hardware for a spin qubit implementation have received attention of a growing community of chemists and physicists.[1] Recent milestones include the combination of a set of addressable nuclear spin states with the possibility of their read out in a single molecule, enabling the experimental realization of a 2-qubit Grover algorithm in a spintronic setup,[2] a proposal to use fast electronic spin excitations to switch the effective interaction between nuclear spin qubits and enable the realization of a two-qubit molecular architecture,[3] and a project for scaling up quantum computation by combining molecular spins with novel microwave superconducting resonators.[4]

In this contribution we will focus on two recent research lines within this field, the first one hardware-oriented and the second one theory-oriented. On the hardware side, the proposal of using of metallo-peptides as versatile platforms for quantum computing[5] has recently expanded to the spintronic setup, with the demonstration of Chirality Induced Spin Selectivity in metallo-peptides in a solid state device.[6] On the theory side, the development of inexpensive computational methods to locate and address the molecular degrees of freedom that are relevant to spin relaxation and thus to qubit decoherence.[7,8]

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Coherence and non-classicality of quantum Markov processes

Although quantum coherence is a basic trait of quantum mechanics, the presence of coherences in the quantum description of a certain phenomenon does not rule out the possibility to give an alternative description of the same phenomenon in purely classical terms. In [1] we give definite criteria to determine when and to what extent quantum coherence is equivalent to non-classicality. We prove that a Markovian multi-time statistics obtained from repeated measurements of a nondegenerate observable can be traced back to a classical statistics if and only if the dynamics is not able to generate coherences and to subsequently turn them into populations (we denote such dynamics as NCGD), a condition that needs to be fulfilled for an infinite amount of time steps $t \geq s \geq r \geq 0$. In particular, we find that, if the considered dynamics is also CP-divisible time-homogeneous, then the fulfillment of only $d(d-1)$ conditions suffices to ensure the dynamics is NCGD [2]. We then apply this result to qubit dynamics to elucidate which kind of qubit noise gives rise to NCGD evolutions. This allows us to find that qubit time-homogeneous rank-one Lindblad noise which is not NCGD (and therefore gives rise to non-classical statistics) turns out to be a valuable resource for quantum metrology. Furthermore, we show with simple examples that the connection between quantum coherence and non-classicality is generally absent if the statistics is non-Markovian [1].

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Quantized Hodgkin - Huxley model for Quantum Neurons

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The Hodgkin-Huxley model describes the behavior of the cell membrane in neurons, treating each part of it as an electric circuit element. We focus on the activation channel of potassium ions, due to its simplicity, while keeping most of the features displayed by the original model. This reduced version is essentially a classical memristor, a resistor whose resistance depends on the history of electric signals that have crossed it, coupled to a voltage source and a capacitor. Here, we will consider a quantized Hodgkin-Huxley model based on a quantum memristor formalism. We compare the behavior of the membrane voltage and the potassium channel conductance, when the circuit is subjected to AC sources, in both classical and quantum realms. Numerical simulations show an expected adaptation of the considered channel conductance depending on the signal history in all regimes. Remarkably, the computation of higher moments of the voltage manifest purely quantum features related to the circuit zero-point energy. This study may allow the construction of quantum neuron networks inspired in the brain function, as well as the design of neuromorphic quantum architectures for quantum machine learning.

Towards long distance entanglement between a photon and a solid-state quantum memory

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As the reach of quantum technologies extends ever further in communication and information science, a reliable way of transferring quantum information between distant locations becomes ever more crucial. While photons are widely accepted as excellent carriers due to their speed and low decoherence, losses of transmission (in free space or fibre) and the impossibility of cloning quantum information still pose a great challenge. The quantum repeater architecture was suggested as a solution to both problems [1]. In a quantum repeater the information encoded in an input state is transferred to a new one through entanglement swapping, that is then sent on along the channel.

In this work we present our advances towards the realisation of a quantum repeater. Our system of choice combines a solid-state quantum memory with a source of photon pairs. The memory is based on a Rare-Earth Doped crystal, where quantum information can be stored in Pr^{3+} ions as a collective excitation using the Atomic Frequency Comb technique. On demand retrieval of the information is realised by transferring the excitation to a long-lived spin state. Record values of storage times and retrieval efficiencies have been demonstrated in this system [2]. Pair of single photons are generated by parametric down conversion in a periodically poled crystal placed inside a bow-tie cavity. This allows us to generate narrow band photons pairs, where the signal is spectrally matched to the memory (606nm), while the idler is in the telecom band [3]. Such a configuration allows us to benefit from the high performance of the memory, while at the same time overcoming the high optical losses of 606nm photons by pair generation of a telecom photon.

The first stepping stone, whose progress is presented in this work, is the successful demonstration of energy-time entanglement between the telecom idler photon and the signal photon, stored as spin-wave excitation. The entanglement analysis will be made through time-bin qubits analyzers made of a fibre-based Mach-Zehnder interferometer, for the former, and a solid-state equivalent based on two AFC with different storage times, for the latter [4]. In this direction we have already doubled the efficiency of the storage protocols, that will be beneficial to count rates and signal-to-noise ratio, as well as improved the spectral-matching between the source and the memory [5]. Demonstration of the successful transfer of quantum information between the signal photon and the long-lived solid-state excitation will open the way to the demonstration of long-distance entanglement between individual nodes in a quantum network.

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Entanglement preserving local thermalization.

Chung Yun Hsieh

We investigate whether entanglement can survive the thermalization of subsystems. We present two equivalent formulations of this problem: 1. Can two isolated agents, accessing only pre-shared randomness, locally thermalize arbitrary input states while maintaining some entanglement? 2. Can thermalization with local heat baths, which may be classically correlated but do not exchange information, locally thermalize arbitrary input states while maintaining some entanglement? We answer these questions in the positive at every nonzero temperature, and provide bounds on the amount of preserved entanglement. We provide explicit protocols and discuss their thermodynamic interpretation: we suggest that the underlying mechanism is a speed-up of the subsystem thermalization process. We also present extensions to multipartite systems. Our findings show that entanglement can survive locally performed thermalization processes accessing only classical correlations as a resource.

Exponentially many monogamy and correlation constraints for multipartite states

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We present an exponentially large family of correlation constraints that apply to all multipartite quantum systems of finite dimension. These constraints stated in terms of linear entropies or purities of reductions. Our relations are obtained by defining and investigating a generalization of the universal state inversion map. This map can, surprisingly, directly be linked to Rains' shadow inequalities [IEEE Trans. Inf. Theory 46, 54 (2000)]. In case of pure states our correlation constraints turn into monogamy relations that govern the distribution of bipartite entanglement in all multipartite quantum systems of finite dimension.

Motivation.—The discussion of entanglement monogamy started more than two decades ago [1]. Its first quantitative formulation was given by Coffman et al. in an equality for distribution of entanglement among three qubits [2], whereas its weaker form, an inequality, was subsequently generalized by Osborne and Verstraete [3] to an arbitrary number of qubits. In the meantime, there have been numerous attempts to generalize the results of Refs. [2, 3] or to find new independent monogamy constraints [4]. Furthermore, it was also found that correlations other than entanglement, such as nonlocality, may obey monogamy relations [5].

It is natural to expect a variety of correlation constraints to exist that originate from the algebraic properties of the density matrix. Based on this intuition, we devise a method to systematically generate an entire family of correlation constraints. Our central result shows that certain positive maps already give rise to an exponential number of independent correlation constraints, as well as to monogamy relations in the case of pure states of any number of parties and finite local dimension. Our method to derive these relations is based on and extends the so-called universal state inversion [7, 8]. This generalized inversion map can, rather surprisingly, directly be linked to Rains' shadow inequalities [9], to which we can now assign a direct physical interpretation.

Generalized state inversion.— Our starting point is the positivity of the following map, which we term generalized state inversion.

Observation 1 *For any n-partite quantum state ϱ of finite local dimensions and all subsets $T \subseteq \{1 \dots n\}$, the following map is positive*

$$\mathcal{I}_T[\varrho] = \sum_{S \subseteq \{1 \dots N\}} (-1)^{|S \cap T|} \operatorname{Tr}_{S^c}[\varrho] \otimes \mathbb{1}_{S^c} \geq 0\,, \tag{1}$$

where S^c denotes the complement of the subset S in $\{1 \dots n\}$.

This claim can be proven by decomposing the above map into individual terms that act on each subsystem j. These have the form

$$(\mathbb{1}_j \otimes \operatorname{Tr}_j - \mathrm{id})[\varrho] = \frac{2}{d_j} \Big(\sum_{k<l}^{d_j-1} \mathsf{y}_{kl}^{(j)}\ [\varrho]^{T_j}\ \mathsf{y}_{kl}^{(j)} \Big)\,, \tag{2}$$

$$(\mathbb{1}_j \otimes \operatorname{Tr}_j + \mathrm{id})[\varrho] = \frac{2}{d_j} \Big([\varrho]^{T_j}\ +\ \sum_{k<l}^{d_j-1} \mathsf{x}_{kl}^{(j)}\ [\varrho]^{T_j}\ \mathsf{x}_{kl}^{(j)}\ +\ \sum_{m=1}^{d_j-1} \mathsf{z}_m^{(j)}\ [\varrho]^{T_j}\ \mathsf{z}_m^{(j)}\ \Big)\,. \tag{3}$$

Above, $\mathsf{y}_{kl}^{(j)}, \mathsf{x}_{kl}^{(j)}$ and $\mathsf{z}_m^{(j)}$ are the Gell-Mann matrices acting on subsystem j (generalizing the Pauli matrices $\sigma_x, \sigma_y, \sigma_z$), the local dimension is denoted by d_j, $[\cdot]^{T_j}$ is the partial transpose and Tr_j the partial trace. This decomposition renders the generalized inversion map $\mathcal{I}_T$ positive, but not completely positive due to the appearance of a global transpose ($\mathcal{I}_T$ is *co-positive*). In the case of $T = \{1 \dots n\}$, the map $\mathcal{I}_T$ is known as the universal state inversion [8].

Alternatively, one may also resort to a result by Rains [9], the so-called shadow inequalities: Let M_1 and M_2 be positive semidefinite operators on $\mathcal{H}_1 \otimes \ldots \otimes \mathcal{H}_N$. Then

$$\sum_{S \subseteq \{1 \dots N\}} (-1)^{|S \cap T|} \operatorname{Tr}\left[\operatorname{Tr}_{S^c}(M_1) \operatorname{Tr}_{S^c}(M_2) \right] \geqq 0\,. \tag{4}$$

Choosing $M_1 = \varrho$, $M_2 = |v\rangle\langle v|$ to be the projector onto an *arbitrary* unit vector, and using the coordinate free definition of the partial trace (namely that $\mathrm{Tr}[M_1 \cdot \mathrm{Tr}_{S^c}(M_2)] = \mathrm{Tr}[M_1 \otimes \mathbb{1}_{S^c} \cdot M_2]$ for all operators M_1 on $\mathcal{H}_S$ and M_2 on $\mathcal{H}_S \otimes \mathcal{H}_{S^c}$) also yields Eq. (1). It is remarkable that Rains' shadow inequalities are directly linked to generalized state inversion, which in turn is connected with correlation and monogamy constraints, as we will show below.

Monogamy of entanglement and correlation constraints.—From the generalized state inversion, a family of correlation constraints follows from the requirement that the expression $\mathrm{Tr}(\varrho\, \mathcal{I}_T[\varrho])$ must be non-negative. Its expansion leads to an inequality applicable to all multipartite states of finite local dimensions and all subsets $T \subseteq \{1 \dots n\}$,

$$- \sum_{S \subseteq \{1 \dots n\}} (-1)^{|S \cap T|} \tau(\varrho_S) \geq 0\,, \tag{5}$$

where $\varrho_S = \mathrm{Tr}_{S^c}(\varrho)$ is the reduction onto subsystem S, and $\tau(\varrho) = \frac{1}{2}[1 - \mathrm{tr}(\rho^2)]$ is the linear entropy.

For a pure state the linear entropy of a subsystem S equals the squared concurrence $C^2_{S|S^c} = \frac{1}{2}[1 - \mathrm{Tr}(\rho^2)]$ over the bipartite split $S|S^c$. This leads to the second main result of our article,

Observation 2 *For any pure multipartite quantum state of finite local dimensions, the following* $2^N - 1$ *monogamy inequalities hold*

$$\mathscr{C}_T(\psi) = - \sum_{\emptyset \neq S \subset \{1 \dots N\}} (-1)^{|S \cap T|}\; C^2_{S|S^c}(\psi) \geq 0\,, \tag{6}$$

Note that one has an inequality for each $\emptyset \neq T \subseteq \{1 \dots N\}$. These inequalities constrain the distribution of concurrence among the subsystems of any global pure state ψ. We stress that there is no ad hoc assumption which underly these constraints, but that they rather follow from the algebraic properties of the generalized state inversion $\mathcal{I}_T$. Because of the apparent analogies of $\mathscr{C}_T(\psi)$ with the distributed concurrence [6], the question arises whether $\mathscr{C}_T(\psi)$ possibly is an entanglement monotone. The answer is: none of the local invariants $\mathscr{C}_T(\psi)$ with $T \neq \{1 \dots N\}$ can be an entanglement monotone.

Consequences & implications.— We introduce a family of positive maps that extends and generalizes the universal state inversion. From it, correlation constraints as well as monogamy relations can be obtained that hold for all multipartite systems having finite local dimensions. Our generalization furthermore unifies approaches from multipartite entanglement and quantum error-correction, assigning a direct physical interpretation to Rains' shadow inequalities that were used to bound the existence of quantum error-correcting codes. Our map can also be used to introduce a a fine-graining of the reduction criterion known from entanglement detection. Lastly, new *operator* constraints for the quantum marginal problem can be derived, which extend the conditions by Butterley et al. [10] for a collection of $(n-1)$-body marginals to originate from a joint state from three qubits to arbitrary multipartite systems.

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Computational complexity of PEPS zero testing.

Sofyan Iblisdir

Projected entangled pair states aim at describing lattice systems in two spatial dimensions that obey an area law. They are specified by associating a tensor with each site, and they are generated by patching these tensors. We consider the problem of determining whether the state resulting from this patching is null, and prove it to be NP-hard; the PEPS used to prove this claim have a boundary and are homogeneous in their bulk. A variation of this problem is next shown to be undecidable. These results have various implications: they question the possibility of a 'fundamental theorem' for PEPS; there are PEPS for which the presence of a symmetry is undecidable; there exist parent hamiltonians of PEPS for which the existence of a gap above the ground state is undecidable. En passant, we identify a family of classical Hamiltonians, with nearest neighbour interactions, and translationally invariant in their bulk, for which the commuting 2-local Hamiltonian problem is NP-complete. Joint work with: Giannicola Scarpa, Yimin Ge, Andras Mólnar, Norbert Schuch, Juan José García Ripoll, David Pérez García.

A method for improving quantum optimization algorithms: the marginals optimization procedure

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Recent algorithmic developments have created new opportunities for achieving quantum advantage. In particular, the variational quantum eigensolver (VQE) algorithm (1) and the quantum approximate optimization algorithm (QAOA) (2) show promise for future industrial application. There are a number of milestones that must be reached to implement useful instances of these algorithms on near-term quantum devices. First, the device needs to bear a sufficiently large number of qubits. Second, the processes, or quantum gates, on the quantum computer need to be of sufficiently high fidelity. Low fidelity quantum gates will output quantum states with degraded coherence, and sufficiently coherent output states are necessary for many of these applications. The performance of algorithms such as VQE and QAOA can, in principle, be systematically improved by including more layers of quantum gates. The number of layers of gates is referred to as the *circuit depth*. Therefore, when executing a quantum algorithm, one seeks to achieve sufficiently large depth of the circuit, while simultaneously minimizing the decoherence of the output state.

Recently, a number of strategies which mitigate error in variational quantum algorithms have been proposed (3) (4) (5). Without improving the specifications of the device, these methods provide algorithms which reduce the effect of faulty device implementation. In this spirit, we introduce a technique which both extends the achievable depth of the quantum circuit and mitigates errors. The technique “algorithmically appends” perfect quantum gates to the output of a variational quantum circuit in order to improve the expressibility, while not detracting from the coherence of the output state. In the fermionic case of VQE, this is achieved in post-processing by applying fermionic linear transformations to the measured reduced density matrix. With respect to the energy estimates, applying these transformations is equivalent to applying a sequence of ideal gates at the end of the quantum circuit, algorithmically extending the depth of the circuit.

This method can be used to extend the capabilities of quantum computers when implementing variational quantum algorithms such as VQE or QAOA. We show simulation data demonstrating the performance of this technique and detail several possible applications and ways it can be integrated with existing techniques.

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Extracting entanglement from the indistinguishability of particles

(SY Lee, J. Ryu, Z. Lasmar, D. Kaszlikowski and P. Kurzyński)

The states of a system of identical particles are required to be symmetric for bosons and antisymmetric for fermions. Are these inherent correlations just a mathematical artifact or can they be treated as a resource? I will support the latter point of view by showing how operationally accessible entanglement can be extracted form the indistinguishability of particles. I will focus on a recently proposed method [1] based on tailored single-photon subtractions from multiboson states.

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Quantum Storage of Frequency-Multiplexed Heralded Single Photons.

Dario Lago Rivera

Quantum memories for light are important devices in quantum information, in particular for applications such as quantum networks and quantum repeaters [1]. Multimode quantum memories able to store independently multiple modes would greatly help the scaling of quantum networks by decreasing the entanglement generation time between remote quantum nodes. Current research focuses mostly on time multiplexing in rare-earth doped crystals and in spatial multiplexing in atomic gases. Beyond these demonstrations, rare-earth doped crystals, thanks to their large inhomogeneous broadening, represent a unique quantum system, which could also add another degree of freedom, the storage of multiple frequency modes [2]. In this contribution, we report on the first demonstration of quantum storage of a frequency multiplexed single photon into a laser-written waveguide integrated in a praseodymium (Pr) crystal.

We use a cavity-enhanced SPDC source to generate frequency multiplexed photon pairs, with one photon in resonance with the transition of the Pr and the other at telecom wavelength. We use the atomic frequency comb protocol [3] to demonstrate storage of the multiplexed heralded single photon. We show that we can store the main part of its spectrum consisting of 15 modes. This leads to an increase of our count-rate by 5.5 with respect to the single frequency mode storage. This high count-rate allows us to make a detailed analysis of the multiplexed-biphoton state after the storage. We study the non-classicality of the stored photons after being stored for 3.5 us. The measured cross-correlation violates the classical bound, as well as the heralded autocorrelation of the stored photons. We show that we are able to increase the non-classicality by lowering the pump-power of the source.

Together with the 9 temporal modes, stored as an intrinsic property of the AFC protocol, we demonstrate the storage of more than 130 individual modes. The ability to combine several multiplexing capabilities in one system would open the door to the realization of massively multiplexed quantum memories.

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Symmetry protection of N-photon angular momentum states when interacting with cylindrical systems

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In the interaction with a cylindrical sample, the *z*-component of the total angular momentum of light, *m*, is a conserved quantity, whereas other quantum numbers are not (as λ, the quantum number related to helicity). Importantly, this helicity-angular momentum framework has allowed the study of quantum light matter interactions in nanoholes, for N = 2 and considering states only with $m = 0$ [1].

In this work we show a generalization of this construction for N-photon states employing single photons with both $m = 0$ and also $m \neq 0$. We find that symmetry protected 2 and 3 photon-states (states that are protected in the interaction with any cylindrical scatterer) can also be found using input modes with $m \neq 0$, even in situations where the input photons are in different modes with different angular momenta.

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Exploring Bell inequalities for the device-independent certification of multipartite entanglement depth

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Techniques developed for device-independent characterizations allow one to certify certain physical properties of quantum systems without assuming any knowledge of their internal workings. Such a certification, however, often relies on the employment of device-independent witnesses catered for the particular property of interest. In this work, we consider a one-parameter family of multipartite, two-setting, two-outcome Bell inequalities and demonstrate the extent to which they are suited for the device-independent certification of genuine many-body entanglement (and hence the entanglement depth) present in certain well-known multipartite quantum states, including the generalized Greenberger-Horne-Zeilinger (GHZ) states with unbalanced weights, the higher-dimensional generalizations of balanced GHZ states, and the W states. As a byproduct of our investigations, we have found that, in contrast with well-established results, provided trivial qubit measurements are allowed, full-correlation Bell inequalities can also be used to demonstrate the nonlocality of weakly-entangled unbalanced-weight GHZ states. Besides, we also demonstrate how two-setting, two-outcome Bell inequalities can be constructed—based on the so-called GHZ paradox—to witness the entanglement depth of various graph states, including the ring graph states, the fully-connected graph states, and some linear graph states etc.

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Coherence and asymmetry cannot be broadcast

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In the presence of conservation laws, superpositions of eigenstates of the corresponding conserved quantities cannot be generated by quantum dynamics. Thus, any such coherence represents a potentially valuable resource of asymmetry, which can be used, for example, to enhance the precision of quantum metrology or to enable state transitions in quantum thermodynamics. Here we ask if such superpositions, already present in a reference system, can be broadcast to other systems, thereby distributing asymmetry indefinitely at the expense of creating correlations. We prove a no-go theorem showing that this is forbidden by quantum mechanics in every finite-dimensional system. In doing so we also answer some open questions in the quantum information literature concerning the sharing of timing information of a clock and the possibility of catalysis in quantum thermodynamics. We also prove that even weaker forms of broadcasting, of which Åberg's 'catalytic coherence' is a particular example, can only occur in the presence of infinite-dimensional reference systems. Our results set fundamental limits to the creation and manipulation of quantum coherence and shed light on the possibilities and limitations of quantum reference frames to act catalytically without being degraded.

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Quantum walks over the honeycomb and triangular lattices

In this work we show how to simulate quantum physical models via discrete-time quantum walks (QWs) over hexagonal and triangular lattices. We show that these simulation results need not rely on the grid: the Dirac equation in (2 + 1)–dimensions can also be simulated, through local unitaries, on the honeycomb or the triangular lattice [1], both of interest in the study of quantum propagation on the non-rectangular grids, as in graphene-like materials.

On the other hand, this model allow us easily to simulate the Dirac equation over discretized curved spacetime applying a transformation over the honeycomb and triangular lattice. We believe that this constitutes an important step towards: modeling propagation in crystalline materials; identifying substrates for QW implementations; studying topological phases and understanding propagation in discretized curved spacetime [2].

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Towards Pricing Financial Derivatives with an IBM Quantum Computer

And the new abstract: Pricing interest-rate financial derivatives is a major problem in finance, in which it is crucial to accurately reproduce the time-evolution of interest rates. Several stochastic dynamics have been proposed in the literature to model either the instantaneous interest rate or the instantaneous forward rate. A successful approach to model the latter is the celebrated Heath-Jarrow-Morton framework, in which its dynamics is entirely specified by volatility factors. On its multifactor version, this model considers several noisy components to capture at best the dynamics of several time-maturing forward rates. However, as no general analytical solution is available, there is a trade-off between the number of noisy factors considered and the computational time to perform a numerical simulation. Here, we employ the quantum principal component analysis to reduce the number of noisy factors required to accurately simulate the time evolution of several time-maturing forward rates. The principal components are experimentally estimated with the 5-qubit IBMQX2 quantum computer for 2×2 and 3×3 cross-correlation matrices, which are based on historical data for two and three time-maturing forward rates. This manuscript is a first step towards the design of a general quantum algorithm to fully simulate on quantum computers the Heath-Jarrow-Morton model for pricing interest-rate financial derivatives. It shows indeed that practical applications of quantum computers in finance will be achievable in the near future.

Certified answers for ordered quantum discrimination problems

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We investigate the problem of quantum discrimination for sets of pure states with an intrinsic ordering. This structured quantum discrimination problems allow a novel scheme that provides a certified level of error, this means, the answers do not deviate from the true value more than a specific distance. We investigate two paradigmatic problems: the Quantum Change Point (QCP) [1] and the Quantum Position Error Identification (QPEI) [2].

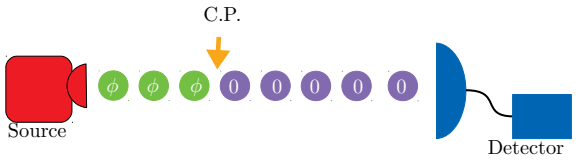

Figure 1: QCP setup.

The Change Point analysis consists in the identification of a sudden change in a signal [3]. A quantum version of this problem is to imagine a machine that produces a specific state and suddenly produces another one. Our task is to identify the point when this happens as depicted in figure (1). The identification scheme that yields the maximum probability of success allowed in quantum mechanics is a global one [1]. This global optimum is reached with a minimum error scheme, this means, allowing errors in all sites. We can consider a global scheme version that admits no errors, this means using the unambiguous scheme [4]. The change point could be detected as it happens with a local measurement or in this case online. This would imply in general a lower success probability but is far more practical to implement. Surprisingly, the online unambiguous give the same success probability as the global unambiguous scheme [5].

The QPEI [2] consists in the identification of a malfunctioning apparatus in a linear array. This problem has an intrinsic ordering as one machine is next to the other in the array, see figure (2). The QPEI can be regarded as a Quantum Anomaly Detection problem [6] which consists in identifying data that is lying out of a given data set using quantum computers or systems. This means, given a data set there can be some subset of data that behave significantly different from the majority of the data, the task is to identify this outliers.

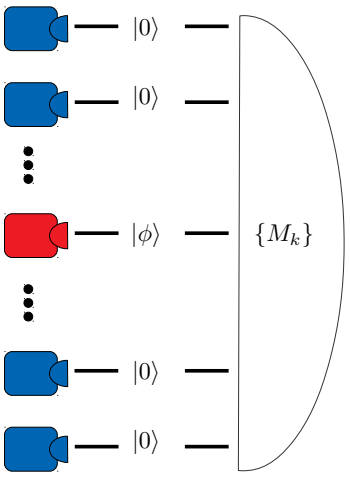

Figure 2: QPEI setup

The usual schemes of quantum discrimination are minimum error and unambiguous discrimination. In unambiguous discrimination no errors are allowed, there is an inconclusive rate. While in minimum error, one always provides an answer, which can be erroneous. In problems where there is a natural ordering one can quantify the distance from the correct quantum hypothesis. We can devise schemes that gives answers with a certified maximum number of distance error. This means that we can implement schemes that allow one or less sites errors, then two or less sites etc. until we get to all possible sites, which coincides with the minimum error scheme. The objective in all cases is to maximize the probability of success.

For this family of schemes we have developed a semidefinite programming (SDP) [7] approach that finds the optimal configuration that yields answers with a certified number of errors. For one error $m = 1$, the SDP is within good approximation, a natural extension of the unambiguous SDP [4]. For $m > 1$ the program is more involved.

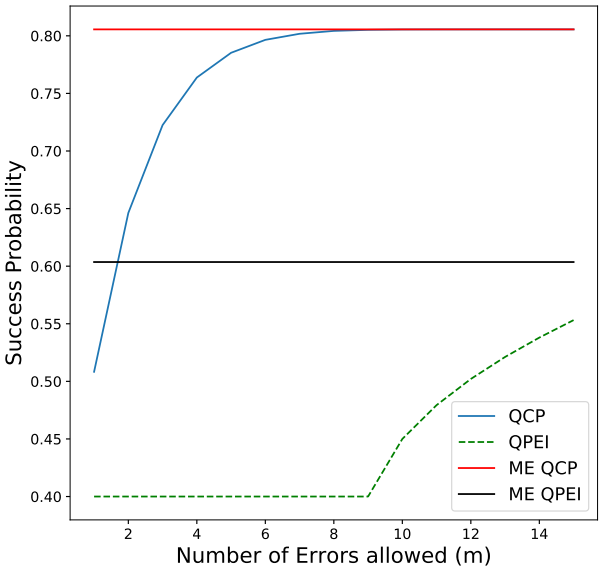

Figure 3: For $N = 20$ particles and $\langle 0|\phi\rangle = 0.6$.

The unambiguous scheme allows no erroneous answers. Allowing errors successively (departing from the unambiguous scheme) can result in substantial incrementation of the probability of success. This is exactly what happens in the QCP. In fact, we can reach the probability of success of the minimum error case with less errors, $m < N - 1$ where N is the total number of quantum hypothesis. The relative gain curve depends on the relevant parameter of this problem which is the overlap $\langle 0|\phi\rangle$. With the QPEI this does not happen, any scheme with $m < N - 1$ yields a lower probability of success, this is shown in figure (3).

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Fluctuation-Dissipation theorem for non-equilibrating dynamics

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The fluctuation-dissipation theorem (FDT) is a central result in statistical physics, both for classical and quantum systems. It establishes a relationship between the linear response of a system under a time-dependent perturbation and time correlations of certain observables in equilibrium. We derive a generalization of the theorem which can be applied to any Markov quantum system and makes use of the symmetric logarithmic derivative (SLD). There are several important benefits from our approach. First, such a formulation clarifies the relation between classical and quantum versions of the equilibrium FDT. Second, and more important, it facilitates the extension of the FDT to arbitrary quantum Markovian evolution, as given by quantum maps. Third, it clarifies the connection between the FDT and quantum metrology in systems with a non-equilibrium steady state [1].

We further investigate fluctuation-dissipation theorem for continuous variable systems. Particularly, we find a linear response theory for quantum Gaussian systems subject to time dependent Gaussian channels. In particular, we establish a fluctuation dissipation theorem for the covariance matrix that connects its linear response at any time to the well-studied elements of Gaussian quantum channels. We show how our results simplify the study of Gaussian systems subject to a time dependent Lindbladian master equation[2].

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Storage of a single photon in a highly non-linear medium based on Rydberg atoms

Photons are very good candidates to carry quantum information due to their negligible interactions. However, photon-photon interactions are needed to process photonic quantum information. This is very useful for quantum repeater applications [1], in which the success probability of entanglement swapping can be highly increased if the Bell-state measurement is performed deterministically. In the case of photons, it requires mapping them in a non-linear medium at the single-photon level. This strong non-linearity has been demonstrated by using Rydberg atoms, which are atoms excited to states with a high principal quantum number. However, previous experiments with Rydberg atoms have been implemented with weak coherent input states of light [2, 3]. Hence, the mapping of true single photons to a medium with single-photon non-linearity is, so far, an outstanding goal. In this work, we have demonstrated a non-linear medium at the single-photon level compatible with the storage of single photons emitted by a quantum memory.

The single photons are generated in a quantum memory following the Duan-Lukin-Cirac-Zoller scheme [4], which is based in a cold atomic ensemble of ^{87}Rb atoms. It generates pairs of correlated photons with a controllable delay between them. One of the photons is then, coupled into a 10 m fibre and sent to a separated cloud of cold ^{87}Rb atoms. There, the photon reaches the atomic cloud with a strong counter-propagating coupling beam which allows the excitation to a Rydberg state (n=60) via electromagnetically-induced transparency. By switching off the coupling beam while the photon travels inside the medium, we can store the photon as a Rydberg excitation and then retrieve it by switching the coupling beam back on.

Our results showed that non-classical correlations between the pair of photons persisted after retrieval from the Rydberg ensemble, as well as the single photon statistics of the stored photon [5]. Although this experiment was carried out with a non-linearity in the Rydberg ensemble at the level of tens of photons, we have lately increased it until the single-photon regime. This has been achieved by loading the atoms in a dipole trap, obtaining a denser and smaller atomic cloud. Experiments aiming at storing a single photon in this medium are under way.

These results represent an important step towards the creation of a building block for deterministic Bell-state measurements in quantum repeaters.

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An open quantum system coupled to an open environment

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A quantum system can be coupled to a larger one that acts as an environment, a fundamental setup used for instance to understand the thermalization of the system when interacting with a thermal bath. But the environment itself can be coupled to another reservoir. The dynamics that arises from this situation can be very rich, depending on the couplings and the different temperatures of both environments. We examine this dynamics, by paying attention to the phenomenon of pre-thermalization, a transitory state in which the quantum system seems to converge to the thermal state of the first environment, but finally tends to the thermal state of the second reservoir.

A method for obtaining extreme points for the set of unital qutrit channels.

Constantino Rodriguez

The set of unital quantum channels on M_d can be decomposed in terms of extreme points. Extreme quantum channels correspond to unitary channels for $d = 2$. Interestingly, for $d > 2$, the existence of non-unitary extreme channels raises the impossibility of a quantum analogue to Birkhoff's theorem. We present a method for obtaining extreme points for the set of unital quantum channels on M_3 by considering an operator-sum representation in terms of the Heisenberg-Weyl basis.

Beyond the swap test: optimal overlap estimation of quantum states

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The swap test is a simple quantum circuit that determines whether two unknown quantum states $|\psi\rangle$ and $|\phi\rangle$ are equal. It constitutes a building block for several applications in quantum information, in particular reference-frame alignment and quantum machine learning, where it is employed to estimate the overlap between two unknown quantum states: given a copy of each state, the swap test performs a projection on the symmetric subspace of the state $|\psi\rangle \otimes |\phi\rangle$ and it is known to provide an optimal estimate of their overlap $|\langle\psi|\phi\rangle|^2$. However, if we are given more copies of the states, the optimal strategy is in general a non-local measurement that entangles all the copies. In this work we consider the problem of estimating the overlap between two states in any Hilbert of finite dimension, given a different number of copies of each of them, i.e., $|\psi\rangle^{\otimes m}$ and $|\phi\rangle^{\otimes n}$. We solve completely the problem in the Bayesian case, providing the optimal estimator and the minimum variance attained by it. Moreover we study the Quantum Fisher Information asymptotically in the number of copies, and show that a joint measurement dramatically improves the estimation with respect to the swap test, particularly in the region of large overlap, where the states are more difficult to distinguish. Similar performance is obtained also with a simpler estimate-and-project protocol. We then prove the robustness of our test with respect to experimental noise, showing that, if the copies are subject to white noise, a corrected strategy is able to achieve optimality. Finally, we present a version of the problem for infinite-dimensional systems.

Molecular Spin Qubit Relaxation Meditated by Spin-vibrational Coupling in Lanthanide Complexes

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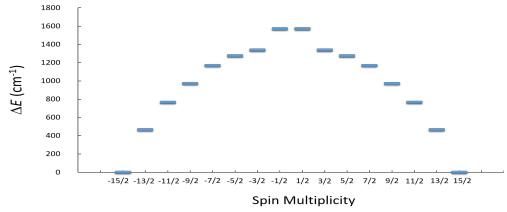
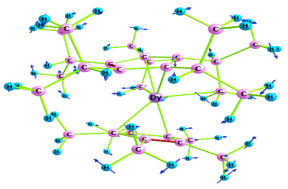
Molecular spin-qubits hold great promise for quantum computing due to their bistable magnetic ground states. Recent advancement in molecular spin-qubits shows that spin-vibrational coupling is the main source for magnetic relaxation, at least, at high temperature and, therefore, limits the quantum coherence. In the context of Electronic Paramagnetic Resonance (EPR), this quantum decoherence is associated with the spin-lattice relaxation time T_1 which eventually acts as an upper limit to the spin-spin relaxation time T_2. To design molecular systems that act as coherent molecular spin-qubits, it is important to quantify the contribution of molecular vibrations to the decoherence process. An intermediate step to this is to evaluate the modulation of the energy levels of the molecular spin-qubit from each vibrational normal mode. These knowledge about the dynamical relaxation with temperature is crucial for a more rational design of novel, enhanced and robust molecular spin-qubits for practical applications. In fact, this is the strategy that has been recently employed for the design of a new single-molecule magnet (SMM), based on dysprosium metallocene complex $[(Cp^{iPr5})Dy(Cp^*)]^+$ (Cp^{iPr5}, penta-iso-propylcyclopentadienyl; Cp, pentamethylcyclopentadienyl)(Dy-5*), which exhibits slow magnetic relaxation up to 80K overcoming the previous record at 60K [1, 2]. Nevertheless, in these studies the theoretical characterization was computationally very demanding with high-level multiconfigurational wave function calculations and other reasonably accurate but affordable approximations are required.

In the present work, we employ a novel and computationally-inexpensive approach to quantify the contribution of each vibrational normal mode to the magnetic relaxation in the Dy-5* SMM [3]. Initially, we have fully optimized the geometry at DFT level and then calculated the vibrational normal modes for Dy-5*. We also retrieved the energy levels for the ground state of Dy-5* ($^6H_{15/2}$) shown in Fig.1a by using a crystal field approximation implemented in the SIMPRE code [4]. For each normal mode (Fig.1b), certain number of distorted geometries are obtained by distorting the equilibrium geometry along each vibrational mode coordinate. Finally, the second derivative of the each crystal field parameter of interest with respect to each mode coordinate are calculated, giving us the thermal evolution of the crystal field parameters as a previous step to access spin dynamics information, such as magnetic relaxation rates at different temperatures and relaxation pathways by each vibrational mode in Dy-5*. The simple and computationally inexpensive approach posed here can be extended to explore other Lanthanide-based complexes and used to assist in the design of novel and improved molecular spin-qubits.



(a)



(b)

FIG. 1. a) Energy spectrum for the $^6H_{15/2}$ ground state of Dy-5* at the DFT-based optimized geometry using SIMPRE. b) Example of a low-frequency normal mode (46.9 cm^{-1}) of Dy-5* contributing to the relaxation of the molecular spin qubit.

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Nonadiabatic Statistical Theory: Application to Spin Relaxation in Single-Molecule Magnets

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Spin-dependent processes mediated by spin-orbit coupling, including intersystem crossings, spin crossovers and spin-forbidden reactions, play important roles in photochemistry, catalysis, and quantum information science. To predict the rates of these processes and the lifetimes of excited electronic states we developed two complimentary theoretical approaches based on nonadiabatic molecular dynamics and statistical theory.[1,2] The direct nonadiabatic dynamics is an ideal tool to study fast photochemical processes, while statistical theory can be applied to slow spin-dependent processes in large complex systems. We will show how the nonadiabatic statistical theory can be used to predict the relaxation rates and excited state lifetimes for relatively slow spin-dependent processes characterized by an energy barrier. The main computational steps include optimizing the minimum energy crossing point (MECP) structure, which is a two-state analog of transition state, predicting the spin-orbit coupling and transition probability between spin states, and calculating the density of rovibrational states. As an example, the application to thermally activated spin-forbidden transitions in the iron-sulfur proteins [NiFe]-hydrogenase and rubredoxin will be demonstrated.

We will describe the extension of our nonadiabatic statistical theory to predict the spin relaxation rates in the lanthanide and transition metal based single-molecule magnets, which can be used to realize molecular spin qubits. The focus will be on the quantum tunneling of magnetization and the mechanisms associated with coupling between the spin and vibrational degrees of freedom (direct, Orbach, and Raman mechanisms).[3] The challenges associated with identifying the relevant vibrational degrees of freedom and locating the minimum energy crossing points between the states with different magnetic quantum number M_S will discussed.

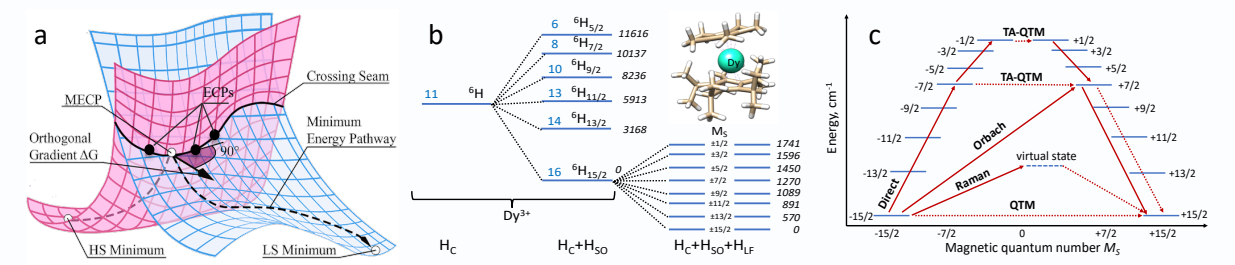

Figure 1. a) Crossing between potential energy surfaces of two spin-diabatic states. The crossing seam and minimum energy path are solid and dashed black lines, respectively. **b**) Energy levels (cm^{-1}) of the dysprosium metallocene complex $[(Cp^{iPr5})Dy(Cp^*)]^+$ calculated with the MCQDPT2 method. **c**) Scheme of different spin relaxation mechanisms.

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Implementation of a controlled-swap gate using structured light

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Abstract: We implement a controlled-swap gate using structured light that carries orbital angular momentum (OAM). The control parameter is the polarization, while the information exchanged is encoded into spatial modes with a given OAM.

The controlled-swap gate is an essential element of the quantum fingerprinting protocol [1], that can determine the degree of overlap between two quantum states and thus evaluate whether they are equal or not. This gate is remarkably difficult to implement experimentally as originally devised, and only with the help of post-selection of appropriate outcomes has been recently implemented a probabilistic version of the protocol [2].

In this work we implement a quantum-inspired version of the controlled-swap circuit using light beams carrying orbital angular momentum (OAM). Our method makes use of the polarization of light as the control bit, which determines the swap operation between OAM beams with opposite m indexes. In our experiment, the information is encoded in the complex amplitudes A_m and B_m of Laguerre-Gauss beams LG^m (index p is assumed to be zero) as

$$\sum_{m=1}^{N} \left(A_m LG^m + B_m LG^{-m} \right)$$

With a measure of polarization of the output beam the method measure the degree of similarity between sequences A_m and B_m, demonstrating in this way that is able to compare streams of data without evaluating the data itself.

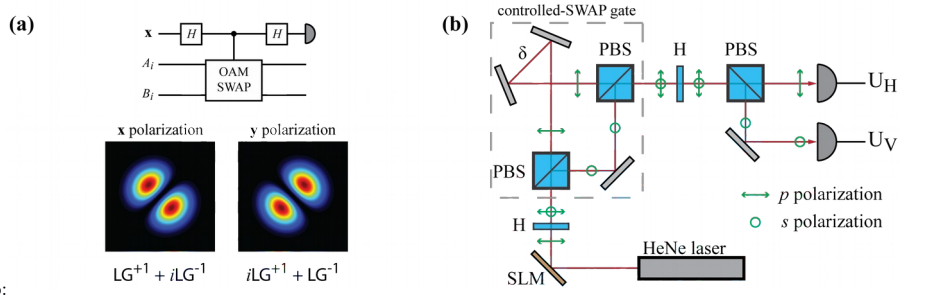

Figure 1. (a) Top: Controlled-swap gate with three inputs and three outputs. *x* and *y* designate orthogonal polarizations, and H is a Hadamard gate (half-wave plate). Bottom: output beam when the input beam is a superposition of two LG beams with OAM of m=1 and m=-1. Their OAM are swapped depending on the polarization. (b) Experimental setup: the structured beam is generated by a spatial light modulator SLM and it enters the controlled-swap gate. The Hadamard gates are implemented with half-wave plates oriented at 45° with respect to the horizontal polarization. The controlled-swap is built up with a polarizing beam splitter cube that splits the beam into their *x* and *y* components. The x polarized beam swaps its OAM at the output of a second *PBS* due to an uneven number of reflections. We measure the polarization of the outgoing beam after a second *H* and a third *PBS*.

The experiment implements the controlled-swap test with an unbalanced polarization-dependent Mach-Zehnder (MZ) interferometer. A superposition of Laguerre-Gauss beams enters the MZ interferometer, where information is encoded in the complex amplitude carried by each LG mode of the superposition. Beams traversing each arm of the interferometer, with orthogonal polarizations, experience a dissimilar number of reflections. The OAM of beams is reversed for an uneven number of reflections and remains the same for an even number of reflections. In order to realize a quantum-inspired quantum fingerprinting protocol, two Hadamard gates have to be implemented in the control bit. In our method, the control bit is the polarization of the light beam, and therefore, the Hadamard gates are easily translated to half-wave plates. Finally, the comparison between both messages (encoded in the complex amplitudes) may be done by projecting the output beam in two orthogonal polarization states. The measured power of each projection is proportional to the overlap between both messages.

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