S7 Quantum Information and Computation
Información y Computación Cuánticas (GEIC)

12/07 Tuesday afternoon, Aula 1.11

15:30-15:45   Alejandro Pozas-Kerstjens, Nicolas Gisin, Marc-Olivier Renou
Proofs of network quantum nonlocality aided by machine learning

15:45-16:00   María Hita-Pérez, Pedro Orellana, Manuel Pino, Juan José García Ripoll
Quasi Bound-State in the continuum in a heavy fluxonium qutrit

16:00-16:15   Paula García-Molina, Javier Rodríguez-Mediavilla, and Juan José García-Ripoll
Quantum Fourier analysis for multivariate functions and applications to a class of Schrödinger-type partial differential equations

16:15-16:30   Pablo Díez Valle
Understanding single-layer QAOA advantage

16:30-16:45   Emanuel-Cristian Boghiu, Flavien Hirsch, Pei-Sheng Lin, Marco Túlio Quintino, Joseph Bowles
Device-independent and semi-device-independent entanglement certification in broadcast Bell scenarios

16:45-17:00   Javier Cerrillo
Transfer-Tensor Method: Analysis and Propagation Tool for Open Quantum Systems

17:00-18:00   **Coffee Break**

18:00-18:15   Javier Argüello-Luengo, Alejandro González-Tudela, Daniel González-Cuadra
Tunable long-range fermion-mediated interactions in cold-atom quantum simulators

18:15-18:30   S. C. Wein, J. C. Loredo, M. Maffei, P. Hilaire, A. Harouri, N. Somaschi, A. Lemaître, I. Sagnes, L. Lanco, O. Krebs, A. Auffèves, C. Simon, P. Senellart, C. Anton-Solanas
On demand time-entanglement in the Fock basis generated by sequential excitation of a two-level atom

18:30-18:45   David Fernández Fernández, Yue Ban, Gloria Platero Coello
Quantum control of two qubits spin hole gates

18:45-19:00   Alberto Castro, Adrián García Carrizo, David Zueco, Fernando Luis
Optimal control of molecular spin qudits

19:00-19:15   Jordi Picó-Cortés, Gloria Platero
Applications of Floquet engineering in ac-driven spin qubits

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Proofs of network quantum nonlocality aided by machine learning

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We formally prove a conjecture initially formulated by using machine learning techniques to identify quantum nonlocality in networks. Quantum nonlocality is a consequence of Bell's theorem, which implies that nature cannot be modeled using only local variables. Both, theoretical advances and experimental improvements, are allowing to move the focus from bipartite settings to scenarios where many independent sources distribute physical systems among different parties in a network.

Nonlocality in networks is defined in a way analogous to the standard notion, namely by opposition to admitting a network-local model. Network-local correlations are those that can be generated by assuming that the sources in the network distribute independent classical shared randomness, and the parties process the randomness they receive to generate an outcome. For example, in the triangle scenario of Fig. 1, local correlations admit models of the form

$$P(a,b,c) = \int \mathrm{d}\alpha \mathrm{d}\beta \mathrm{d}\gamma\, \mu_{BC}(\alpha)\mu_{AC}(\beta)\mu_{AB}(\gamma)$$
$$\times P_A(a|\beta,\gamma)P_B(b|\gamma,\alpha)P_C(c|\alpha,\beta), \qquad (1)$$

where α, β and γ denote sources of classical shared randomness distributed with densities $\mu_{BC}(\alpha)$, $\mu_{AC}(\beta)$ and $\mu_{AB}(\gamma)$, respectively, and P_A, P_B and P_C represent local operations on the variables received by each party.

Recently, an interesting family of quantum distributions in the triangle scenario was proven not to admit triangle-local models for a certain range of its defining parameter [1]. Due to its interest in the field, Ref. [2] analyzed triangle nonlocality in the family by means of deep learning techniques. Surprisingly, this approach lead the authors to conjecture that the family of distributions of Ref. [1] did not admit models of the form of Eq. (1) well beyond the limits established by the original proof (see Fig. 1). However, the inherent features of the formalism of deep learning prevent this conjecture to become a rigorous demonstration.
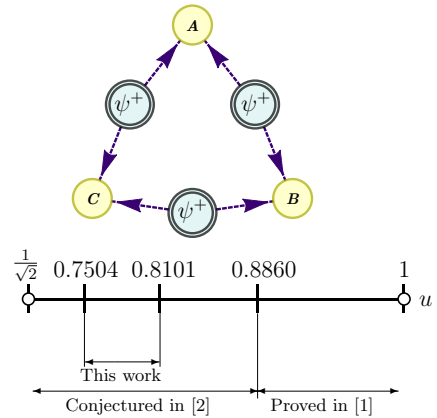

Figure 1. (Top) The triangle scenario, where we look for classical realizations of the quantum probability distributions described in Ref. [1], which are parameterized by $1/\sqrt{2} \le u \le 1$. (Bottom) The current standing of proofs of nonlocality for the family of distributions.

In this work [3], we prove the conjecture formulated in Ref. [2] for a certain range of the parameter characterizing the family of distributions. We do so by reducing the original four-outcome distributions to families of two-outcome ones, and analyzing if these admit local models using the inflation technique [4]. Our construction provides a large family of network Bell inequalities that can contribute in deciding another long-standing open question, namely whether the binary-outcome triangle scenario without inputs supports network nonlocality. More broadly, our results can be framed in the context of artificial intelligence augmentation, which views machine learning as an enabling tool, rather than an automated solver. In this picture, the machine learning approach of Ref. [2] pointed to an interesting question, which in turn has produced results that have increased our understanding of triangle nonlocality, and provided paths for advancing other problems in the field.

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Quasi Bound-State in the continuum in a heavy fluxonium qutrit

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Quantum excitations generally decay when coupled to a band of states with a continuous spectrum, however, there are some exceptions to those decay processes where a confined state lying at the continuum part of the spectrum lives forever. Those bound states in the continuum (BIC) were predicted long ago and have appeared on several platforms as solid-state devices or photonic devices. Some recent works have found BICs modes in typical quantum-information set-ups, such as superconducting circuits, and argue their usefulness for quantum information applications. In this case, BICs correspond to plasma excitations spatially localized in a superconducting waveguide, while a qubit is used to enforce the necessary boundary conditions.

In this talk, we show how to construct a BIC state [1], more precisely a quasi-BIC state, localized within a fluxonium device when it is capacitively coupled to a waveguide [2]. First, we introduce an effective model for the Hamiltonian, flux, and charge operators of the fluxonium qutrit, obtained via an analytical approach based on Gram-Schmidt orthogonalization and with numerical methods. Then, we analyze the capacitive coupling to a waveguide, finding that the second excited state only decays to the first excited, which is a transition that can be strongly suppressed using a large shunting capacitance for the fluxonium.
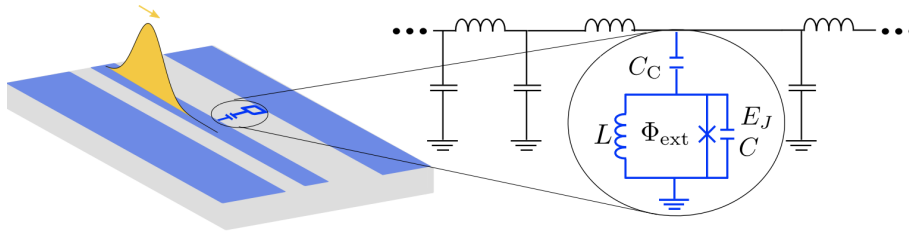

Figure 1. Fluxonium qubit capacitively coupled to a superconducting waveguide.

[1] M. Hita-Pérez, P. Orellana, J.J. García-Ripoll, and M. Pino "Quasi Bound-State in the continuum in a heavy fluxonium qutrit", *in preparation.*
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Quantum Fourier analysis for multivariate functions and applications to a class of Schrödinger-type partial differential equations

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In quantum numerical analysis quantum computers assist in the resolution of numerical analysis problems, among which partial differential equations (PDEs) stand out. Although highly-efficient methods to solve them have been proposed [1], they are not adequate for current noise intermediate-scale (NISQ) devices. Variational quantum algorithms [2] arise as an suitable alternative due to their lower hardware requirements and noise resilience. In this paradigm, a variational quantum circuit encodes the solution to a complex problem (a PDE in our case) and the parameters of the circuit are tuned through a learning process that optimizes a loss function. Both fault-tolerant and NISQ algorithms for quantum numerical analysis need an efficient representation of functions and differential operators. In this work [3], we propose a Fourier encoding to map functions and differential operators to the states of an n-qubit quantum register, whose representation can be extended with quantum Fourier interpolation [4]. Combined, both tools provide an efficient representation, with errors that can decrease doubly exponentially in the number of qubits. This favorable scaling motivates the application

of these ideas on NISQ hardware, transforming the PDE into a variational principle that can be optimized using both existing and novel space-efficient variational *Ansätze* [5, 6], that take into account a problem's symmetries, and global and gradient-based optimizers.

We consider PDEs of the form $[D(-i\nabla) + V(\mathbf{x})] f(\mathbf{x}) = Ef(\mathbf{x})$, defined over a regular domain, with periodic boundary conditions and real functions $D(\mathbf{p}), V(\mathbf{x}) \in \mathbb{R}$. We assume that the PDE is a lower-bounded Hamiltonian operator $H = D(-i\nabla) + V(\mathbf{x}) \geqslant E_{\min}$, and we seek the ground state $E_{\min}$ using a variational quantum algorithm suitable for solving static PDEs with a Hamiltonian nature. We test our method for the PDE of the one-dimensional quantum harmonic oscillator, reaching low infidelities of order $10^{-4}-10^{-5}$ using only 3 to 4 qubits (Fig. 1(a)), demonstrating the high compression of information in a quantum computer. Practical fidelities are limited by the noise and the errors of the evaluation of the cost function in real computers, but they can also be improved through error mitigation techniques, recovering the ideal energy with an error ε of $O(10^{-2})$ (Fig. 1(b)).
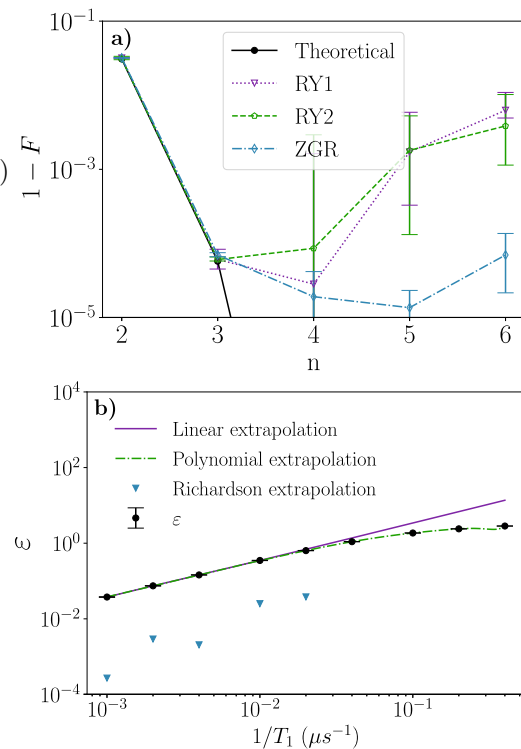
Figure 1. Harmonic oscillator results. (a) Lowest infidelity $1 - F$ for $n = 2, 3, 4, 5, 6$ qubits using the ZGR [5,6] and the R_Y *Ansätze* with depths 1 (RY1) and 2 (RY2). (b) Zero-noise extrapolation for the energy error ε (RY1 with thermal relaxation and 3 qubits).

[1] D. W. Berry, *J. of Phys. A* **47**, 105301 (2014).
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[3] P. García-Molina et al., *Phys. Rev. A* **105**, 012433 (2022).
[4] J. J. García-Ripoll, *Quantum* **5**, 431 (2021).
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Understanding single-layer QAOA advantage

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The Quantum Approximate Optimization Algorithm (QAOA) was originally proposed as a hybrid variational algorithm suitable for solving combinatorial optimization problems on NISQ devices [1]. Even though it has been shown, from reasonable theoretic assumptions, that the shallowest version of the algorithm already engineers a quantum probability distribution that is classically hard to sample [2], this formal sampling advantage may or may not translate into a practical advantage in the optimization scenario. In our work [3], we study a simple, single-layer generalization of the QAOA ansatz, and we analize its performance both from the optimization point of view—i.e. the probability to find the ground state— and also by understanding the types of states it prepares—i.e. the probability distributions that are hard to sample, according to [2].

With a new theoretical approach, our study reveals that the shallowest QAOA on universal Ising spin models creates pure, but thermal-like states with Gaussian perturbations (see Fig.1a). The sampling advantage manifests itself in the fact that these states resemble Boltzmann distributions with a temperature lower than can be efficiently simulated classically according to state-of-art techniques, such as Markov Chain Monte Carlo algorithms (see Fig.1b). Moreover, we connect the sampling advantage and the optimization properties, presenting that this low temperature also implies an advantage with respect to optimization, because there is an algebraic (Grover-like) enhancement of the ground state probability.

We believe that, in addition to opening new avenues for proving quantum advantages, the tools in this manuscript may shed light on more complex circuits, as well as offer new methods to understand the behavior of adiabatic quantum computers and quantum simulators.
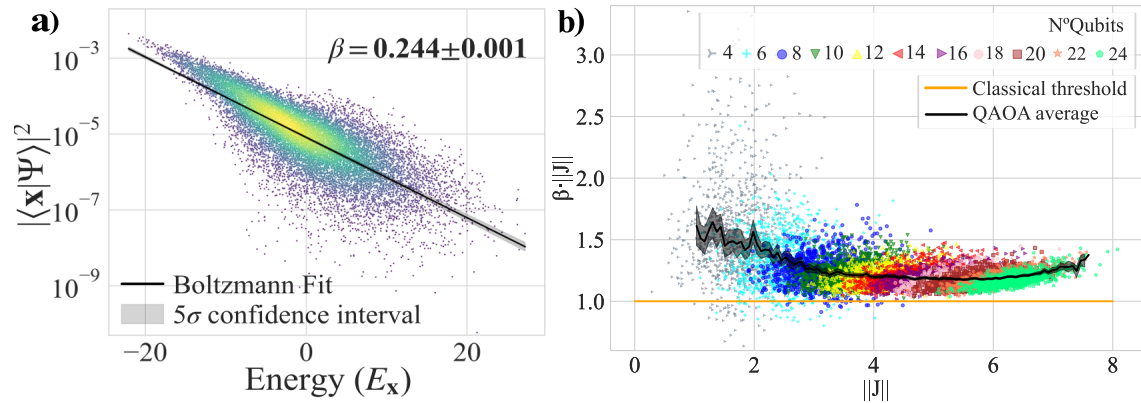

Figure 1: (a) Eigenstate probabilities (dots) and fitted Boltzmann distribution (line) for single-layer QAOA ansatz with optimal angles. (b) Effective temperatures β as a function of the interaction matrix J norm for Sherrington-Kirkpatrick problems. We show the average of these results (black line) and the threshold given by Monte Carlo methods (orange line) which demonstrates that the distributions obtained with one-layer QAOA are hard to sample classically.

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Device-independent and semi-device-independent entanglement certification in broadcast Bell scenarios

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One of the most fascinating aspects of quantum theory is that it does not obey the same common-sense form of causality that is observed at the macroscopic level. Consider an entangled quantum system that is prepared and shared between several spatially separated laboratories and then measured. Remarkably, the correlations between measurement outcomes defy explanation via shared classical resources alone: a phenomenon called Bell nonlocality. Aside from foundational implications, Bell nonlocality plays a key role in quantum information technologies: it serves as fuel for device-independent protocols. The most basic of these protocols is that of entanglement certification: since Bell nonlocality requires the use of entangled states, its observation implies a certificate of entanglement in the underlying physics. Device-independent entanglement certification is highly desirable as it allows us to ensure entanglement even when the measurements performed by parties are untrusted and uncharacterised.

It is known that entanglement alone is not sufficient to observe Bell nonlocality, since some mixed entangled states are known to admit so-called local hidden-variable models. For example, the isotropic state (local unitary equivalent to the two-qubit Werner state),

$$\rho(\alpha) = \alpha|\Phi^+\rangle\langle\Phi^+| + (1-\alpha)1/4,$$

is entangled for $\alpha > \frac{1}{3}$, however, it cannot violate any Bell inequality for $\alpha \lessgtr 0.683$. An important discovery in this respect was that of activation. The basic message is as follows: some quantum states that show only classical behaviour in the orthodox "standard scenario" can have their non-classicality activated, or revealed, by subjecting the state to a more complex measurement scenario. This both expands the set of entangled states that exhibit non-classical behaviour, and rekindles the hope of proving Bell nonlocality of all entangled states. There are a number of different techniques that have been shown to activate quantum states.

In this work we focus on a technique called broadcasting (Figure 1) and show through semidefinite programming techniques that device-independent entanglement certification is possible for the two-qubit Werner state in essentially the entire range of entanglement ($\alpha > 0.338$). To get the same results with other techniques one needs at least 2515 copies of the quantum state and to perform entangling measurements, while with broadcasting we only need 1 copy of the state, local measurements and 2 quantum channels. This makes it much more experimentally friendly. In this work we also construct Bell inequalities tailored to the broadcast scenario, and show how broadcasting can lead to stronger notions of Bell nonlocality activation. In particular, we exploit these ideas to show that bipartite states admitting a local hidden-variable model for general (POVM) measurements can lead to genuine tripartite nonlocal correlations. Finally, we extend the concept of EPR steering to the broadcast scenario, and present novel examples of EPR steering activation of the two-qubit isotropic state.
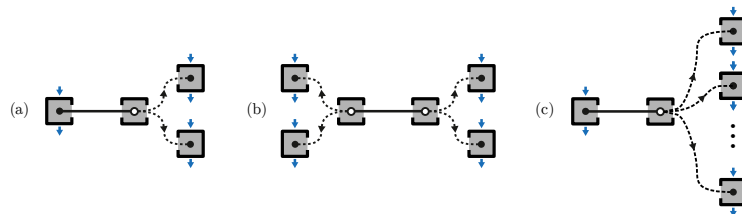

Figure 1. The broadcasting scenario. One (or more) of the local systems is broadcast via the application of a quantum channel, resulting in a multipartite state, sent to distant parties. Local measurements are performed on this state, and the resulting statistics are used to rule out a local hidden variable description for the original bipartite state.

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Non-Markovian Dynamical Maps: Analysis Tool for Open Quantum Systems
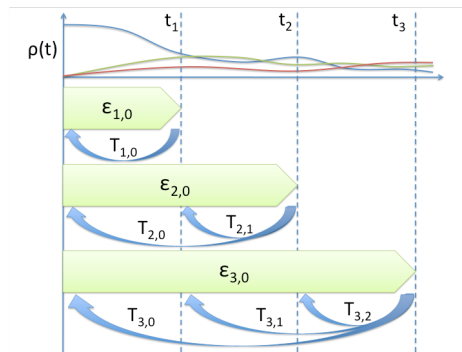
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The effect of an environment on an open quantum system is fully described by the memory kernel in the terms presented in the Nakajima-Zwanzig formalism. It contains the key information of its interaction with the environment and, together with the Hamiltonian, it is sufficient to predict the trajectory at later stages. Its computation in realistic settings is nevertheless impractical and it has historically remained a formal result.

We proposed [1] a general approach based on non-Markovian dynamical maps to extract full information from the initial trajectories of a system and compress it into non-Markovian transfer tensors. The non-Markovian transfer tensor method (TTM) is equivalent to solving the Nakajima-Zwanzig equation and, therefore, can be used to reconstruct the dynamical operators (the system Hamiltonian and memory kernel) from quantum trajectories obtained in simulations or experiments and also to accurately and efficiently propagate the state of the system to arbitrarily long time scales.

The concept underlying the approach can be generalized to physical observables such as absorption [2] and emission spectra [3] with the goal of learning and manipulating the trajectories of an open quantum system. From this perspective, it is possible to relate engineered control and steering mechanisms to its corresponding memory kernel so as to determine the architecture of their physical implementations.

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Tunable long-range fermion-mediated interactions in cold-atom quantum simulators

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Engineering and controlling long-range interactions between ultra-cold atoms would allows to obtain unprecedented many-body phases, such as supersolid [1], magnetic [2,3] and topological ones [4,5], as well as enabling the simulation of quantum chemistry [6] and high-energy problems [7]. Unfortunately, this constitutes an outstanding challenge since atoms generally interact locally via collisions. A way of going beyond this limitation is by using Fermi-Bose mixtures, where fermionic atoms can act as mediators, giving rise to long-range RKKY-type interactions characterized by the dimensionality and density of the fermionic gas. Such interactions have very recently been realized experimentally [8,9] confirming the feasibility of that approach. Here, we propose several tuning knobs, accessible in current experimental platforms, that allow to further control the range and shape of the mediated interactions, extending the existing quantum simulation toolbox. In particular, we include an additional optical lattice for the fermionic mediator, as well as anisotropic traps to change its dimensionality in a continuous manner (see Figure 1). This allows us to interpolate between power-law and exponential decays, introducing an effective cutoff for the interaction range, as well as to tune the relative interaction strengths at different distances. Finally, we show how our approach allows to investigate frustrated regimes that were not previously accessible, where symmetry-protected topological phases as well as chiral spin liquids emerge [10].
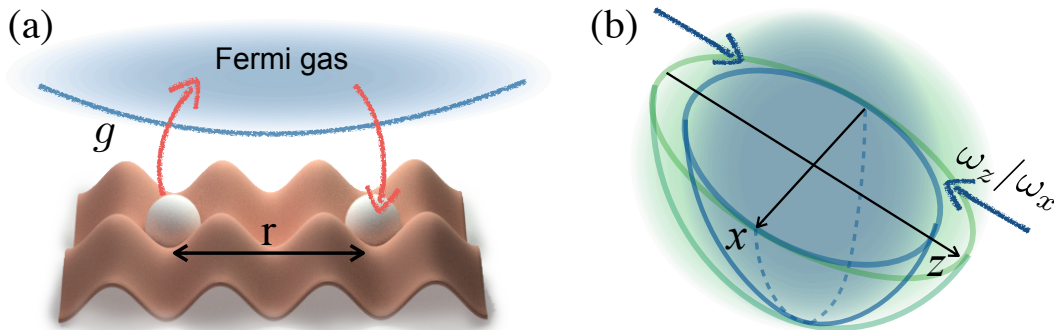

Figure 1. (a) Two bosonic atoms (white) separated by distance r and trapped in an optical lattice (red) experience an effective long-range interaction mediated by a Fermi gas trapped in an harmonic potential (blue). The contact Bose-Fermi interactions (g_{bf}) virtually populates the conduction band of the Fermi gas. (b) By controlling the strength of the trapping potential in an orthogonal direction, ω_z/ω_x, one can continuously tune the dimension of the Fermi gas from 1D to 2D, introducing additional modulating frequencies.

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On demand time-entanglement in the Fock basis generated by sequential excitation of a two-level atom

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During the spontaneous emission of light from an excited two-level atom, the atom briefly becomes entangled with the photonic field, producing the entangled state $\alpha|e, 0\rangle + \beta|g, 1\rangle$, where g and e are the ground and excited states of the atom, and 0 and 1 are the vacuum and single photon states [1].

With a very simple protocol, we experimentally show that the spontaneous emission can be used to deliver on demand photon-number entanglement encoded in time. By exciting a charged quantum dot (an artificial two-level atom) with two delayed π pulses, we generate a photon-number Bell state $\alpha|00\rangle + \beta|11\rangle$, see a sketch of the protocol and the emitted wavepacket in Fig. 1. We characterise the quantum properties of this state using time-resolved photon-correlation measurements [2].

We theoretically show that applying longer sequences of π pulses to a two-level atom produces multipartite entangled states with properties linked to the *Fibonacci* sequence. We believe that these new photonic states could have applications in quantum technology. Additionally, our excitation protocol could be applied on other energy level systems, such as the biexciton-exciton cascade, to produce high-dimensional entanglement.
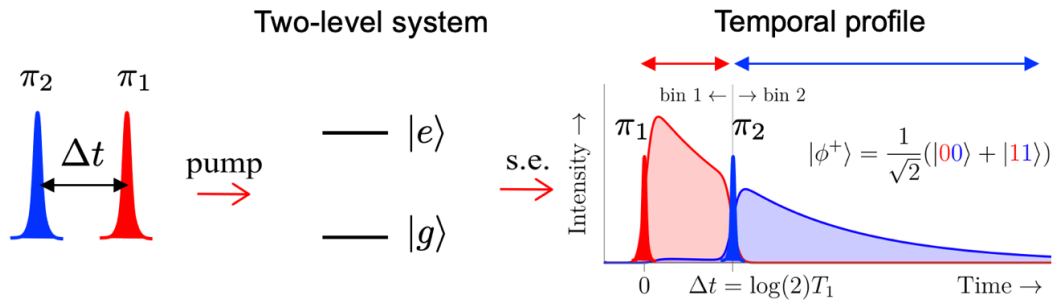

Figure 1. Schematic representation of the double π pulse excitation on a two-level system. The first [second] π-pulse excites the two-level atom at $t = 0$ [$t = log(2)T_1$], the emitted photonic wavepacket is a time-entangled Bell state: the first [second] temporal bin is encoded in a red [blue] color. The vacuum and single photon states are distributed in these time bins generating the Bell state $|\phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$.

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Quantum control of two qubits spin hole gates

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Hole spins in semiconductor quantum dots (QDs) are attracting significant attention as candidates for fast, highly coherent, spin qubits [1-4]. They have long coherence time due to the weak hyperfine coupling to nuclear spins and have demonstrated to have rapid operation times due to the inherently strong spin–orbit coupling (SOC).

In this work we investigate how to control a two-hole spin qubit consisting of a triplet and a singlet hole states. For that purpose, we implement a driving protocol based on Shortcuts to Adiabaticity (STA), minimizing noise effects while enhancing robustness [5, 6]. We consider the fast quasi-adiabatic (FAQUAD) approach and analyze its feasibility to manipulate hole spin qubits and compare with other alternative protocols. We can initialize the qubit in an arbitrary state and perform a NOT gate by changing the detuning between dots. In addition, we achieve a SWAP-like two-qubits gate with a fidelity beyond error correction threshold. We study the robustness of the protocol regarding systematic errors in the detuning, as well as charge noise [7].

Furthermore, we study the direct transfer of entangled holes in QD arrays between edge sites by using inverse engineering techniques. We demonstrate that spin-conserving and spin-flipping direct transfer between edges can be achieved in a controlled way with all-electrical protocols by dynamically tuning the tunnelling rates between dots [8].
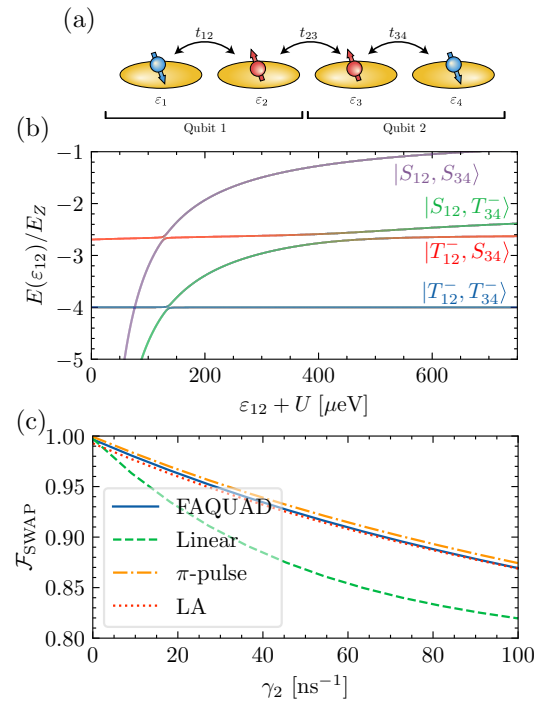

Figure 1. (a) Schematic picture of a quadruple quantum dot encoding two S-T qubits. (b) Energy level diagram of the system. (c) Fidelity of a SWAP gate against charge noise for different protocols.

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# Optimal control of molecular spin qudits

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We demonstrate, numerically, the possibility of manipulating the spin states of molecular nanomagnets with shaped microwave pulses designed with quantum optimal control theory techniques. The state-to-state or full gate transformations can be performed in this way in shorter times than using simple monochromatic resonant pulses. This enhancement in the operation rates can therefore mitigate the effect of decoherence. The optimization protocols and their potential for practical implementations are illustrated by simulations performed for a simple molecular cluster hosting a single Gd^{3+} ion. Its eight accessible levels (corresponding to a total spin $S = 7/2$) allow encoding an 8-level qudit or a system of three coupled qubits. All necessary gates required for universal operation can be obtained with optimal pulses using the intrinsic couplings present in this system. The application of optimal control techniques can facilitate the implementation of quantum technologies based on molecular spin qudits.
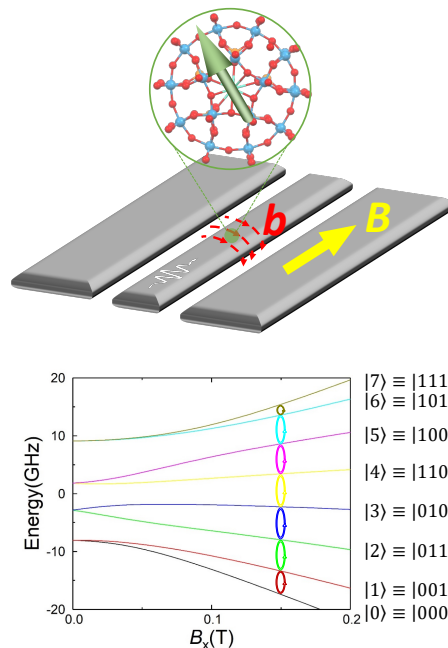
Top: Schematic image of a molecular spin subject to a static magnetic field $\vec{B}$ and to an arbitrarily shaped microwave magnetic field $\vec{b}$, here generated by a transmission line. *Bottom*: spin energy levels of the GdW_{30} polyoxometalate cluster, whose structure is shown in the top. The 8 spin states, associated with the $S = 7/2$ spin of the central Gd^{3+} ion, enable encoding a $d = 8$ qudit or three qubits. The coloured circular arrows mark the seven transitions that can be implemented by means of resonant monochromatic pulses.

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Applications of Floquet engineering in ac-driven spin qubits

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Quantum dots (QDs) offer a powerful platform for quantum computation due to the possibility of employing well known solid-state architectures inherited from semiconductor electronics. In recent years, experiments on QD arrays have showcased the possibility of increasingly complex protocols for manipulation of QD-based qubits, but decoherence due to a noisy environment has remained a key issue. One promising venue for improvement is the use of ac gates in order to tune the properties of the QD arrays, in what is often called Floquet engineering. Here, we discuss two recently developed applications of ac gates for the manipulation and distribution of QD-based qubits. First, we show the possibility of employing the interference between the different photoassisted paths in ac driven QDs to suppress unintended processes. This allows us to develop a protocol to transfer entangled electron pairs between distant quantum dots [1]. Second, we describe a method for increasing the resistance of two-electron qubits to electric noise by inducing a second-order sweetspot in which the dephasing time due to electric noise is zero up to third order in the coupling between the electrons and the environment [2]. These applications showcase the possibilities of ac-based techniques in quantum technologies.

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