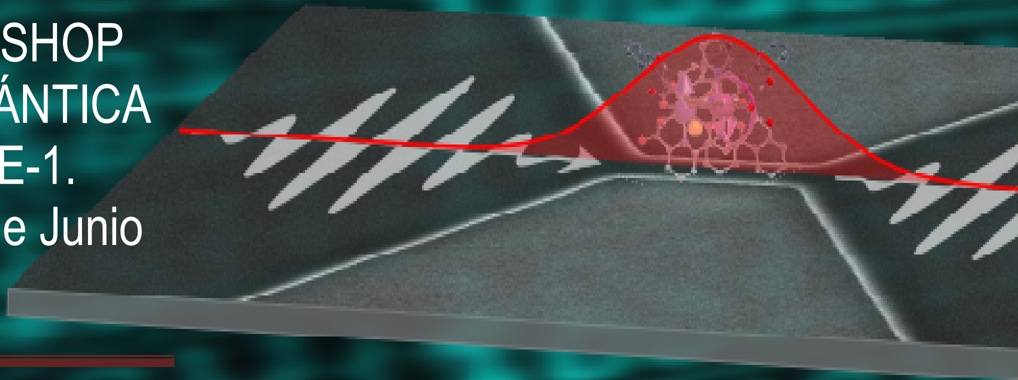
SEGUNDO WORKSHOP
INFORMACIÓN CUÁNTICA
EN ESPAÑA, ICE-1.
Zaragoza, 25 a 27 de Junio
2014



E-BOOK OF ABSTRACTS

Instituto de Ciencia de Materiales de Aragón

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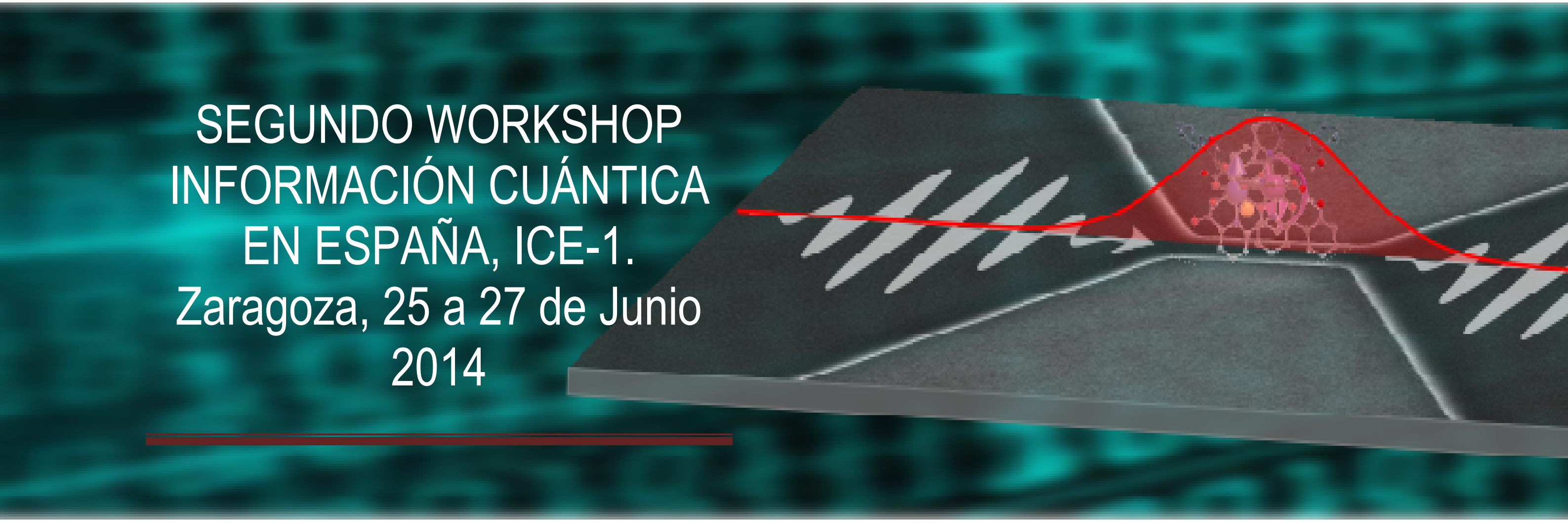

Wednesday, June the 25th 2014
Sala de grados, Facultad de Ciencias (A)

Entanglement of atomic spins beyond simple spin squeezing

(Invited)

Robert Sewell

Instituto de Ciencias Fotónicas

I describe our recent work in generating exotic entangled states in a sample of laser-cooled atomic spins. We use quantum non-demolition (QND) measurement techniques [1] to prepare entangled spin states. In the simplest case, we measure a single spin component and generate spin-squeezing in a sample of highly polarised atoms - a useful resource for quantum-enhanced atomic magnetometry [2]. More recently, we have developed techniques for squeezing all three spin components of an unpolarised sample of atoms. This generates a highly entangled macroscopic spin singlet (MSS) [3,4], analogous to the ground state of many fundamental spin models in condensed matter physics. The state we generate is SU(2) invariant, so it is directly useful for background-free measurement of magnetic field gradients, and may be useful for quantum information tasks such as storing information in a decoherence free subspace. Combining this with quantum feedback control [5] should allow us to deterministically prepare a MSS. In the outlook I discuss prospects for using these techniques for quantum state engineering of quantum lattice gases [6].

[1] Nat. Photon. 7, 517 (2013).
[2] PRL 109, 253605 (2012).
[3] NJP 12, 053007 (2010).
[4] arXiv:1403.1964 [quant-ph].
[5] Phys. Rev. Lett., 111,103601 (2013).
[6] PRA 87, 021601 (2013).

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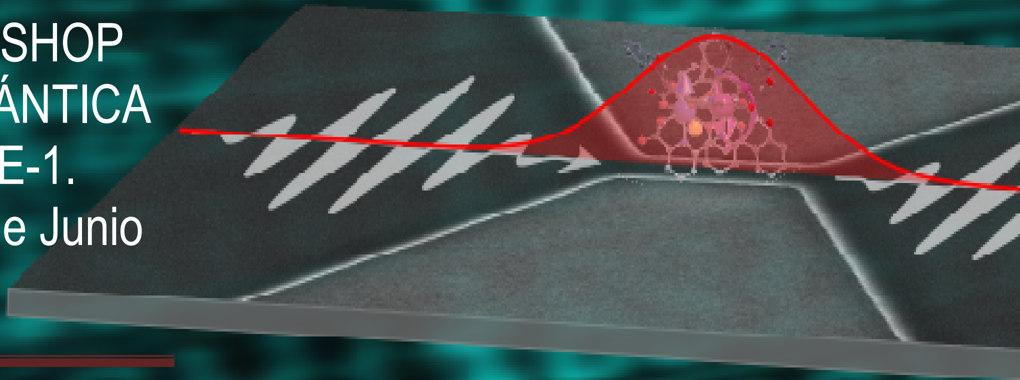
SEGUNDO WORKSHOP INFORMACIÓN CUÁNTICA EN ESPAÑA, ICE-1. Zaragoza, 25 a 27 de Junio 2014



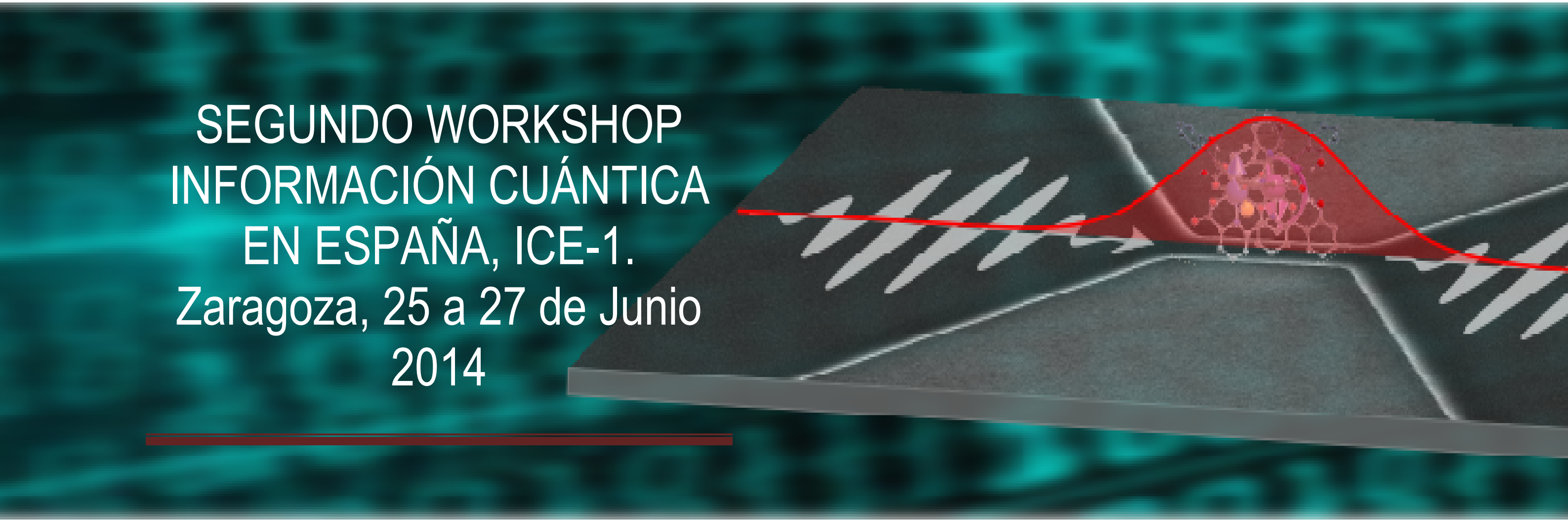
Controlled rephasing of collective spin excitations in cold atom quantum memories for temporally multiplexed quantum repeaters

Pau Farrera[a], Boris Albrecht[a], Matteo Cristiani[a] and Hugues de Riedmatten[a,b]

[a] *ICFO-The Institute of Photonic Sciences*
[b] *ICREA-Institució Catalana de Recerca i Estudis Avançats*

Quantum memories (QM) for light, which allow a coherent and reversible transfer of quantum information between light and long lived matter quantum bits, are crucial devices in quantum information science [1]. In particular they enable to interface stationary quantum bits (encoded in atom-like systems) and flying qubits (encoded in photons). QMs are for example needed for the implementation of ultra-long distance quantum communication using quantum repeater architectures [2]. An important capability for quantum memories is the ability to store multiple qubits at the same time and retrieve them selectively. Laser cooled atomic gases are currently one of the best systems for QM applications, but so far temporal multiplexing with quantum information has not been achieved in these systems. In this contribution, we show a significant step towards achieving this goal. Our experiment is based on a type of QM that has proven to be one of the most advanced quantum repeater building blocks [3], and consists on a laser cooled Rubidium atomic ensemble where we create correlated photon pairs. One of the photons is directly emitted while the other one can be stored in the form of a single collective atomic spin excitation (spin wave) before being mapped into a single photon. Applying a controlled and reversible dephasing to the spin wave allows the creation of photon-spin pairs in different temporal modes and to map into a single photon only the desired spin excitation [4]. So far we have been able to observe the controlled dephasing and rephasing of single spin waves. This has allowed us to perform a selective mapping into photons between collective single spin excitations created at two different times in the same atomic ensemble. Our next goal is to use this system to demonstrate the operation of a building block for a temporally multiplexed quantum repeater protocol, which promises a significant rate enhancement.

[1] H. J. Kimble, “The quantum internet”, Nature 453, 1023–1030 (2008).
[2] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, “Quantum repeaters based on atomic ensembles and linear optics”, Rev. Mod. Phys. 83, 33–80 (2011).
[3] L.-M. Duan, M. D. Lukin, J. I. Cirac and P. Zoller, "Long distance quantum communication with atomic ensembles and linear optics", Nature 414, 413-418 (2001).
[4] C. Simon, H. de Riedmatten and M. I. Afzelius, "Temporally multiplexed quantum repeaters with atomic gases", Phys. Rev. A 82, 010304(R) (2010).



Detecting multiparticle entanglement with spin squeezing inequalities.

G. Tóth[a,b,c]***, G. Vitagliano***[a]

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[b]*IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain*
[c]*Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary*

We study the problem of detecting entanglement and its depth in systems composed of very many particles. We derive entanglement criteria based only on few easy measurable quantities such as the mean values and variances of collective spin components. In particular we present what we call a generalized spin squeezing parameter, that can be used to detect a class of states wider than the spin squeezed states. Moreover we present a criterion to estimate the entanglement depth that outperforms previous well-known criteria. It has been used in a recent experiment to prove that the produced Dicke-like state had an entanglement depth of at least 28 particles.

Entanglement entropy in fermionic chains.

(Invited)

F. Ares, J.V. Esteve, F. Falceto

Departamento de Física Teórica. Fac. de Ciencias. U. Zaragoza
Instituto de biocomputación y física de sistemas complejos. U. Zaragoza.

We present a few results on the Renyi entanglement entropy for stationary states in a homogeneous, quantum, fermionic chain. We first discuss the case of an interval, where analytical tools for the computation are available. We find that, for certain states, one obtains a volume law and possible logarithmic subdominant corrections. By introducing non local interactions in the chain, we can consider the previous as the ground states of fermionic ladders, which leads to a natural physical interpretation for the scaling properties of the entanglement entropy and its universality. Then we move on to the case of several intervals and present a new expression for the asymptotic behaviour of the entanglement entropy. We support our result with clear numerical evidences. This leads to a mathematical conjecture on the asymptotic behaviour of principal submatrices of a Toeplitz matrix.

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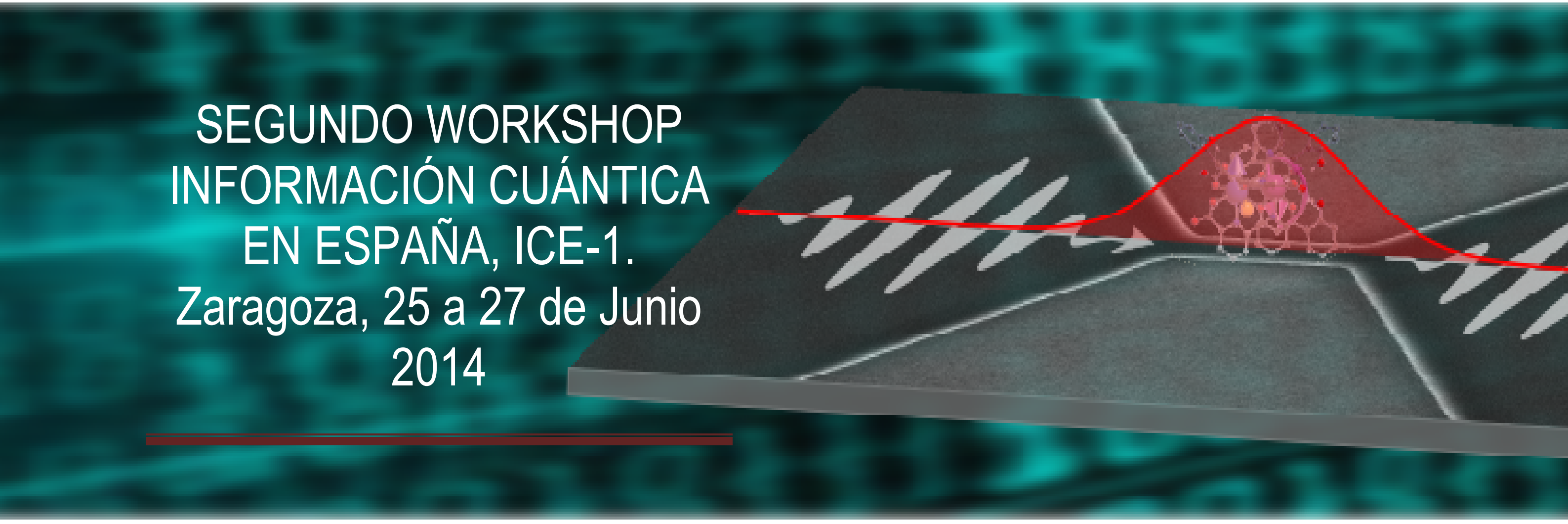


Trapped ion spin-phonon chains: frustrated phases and applications in quantum metrology

(Invited)

Diego Porras

University of Sussex

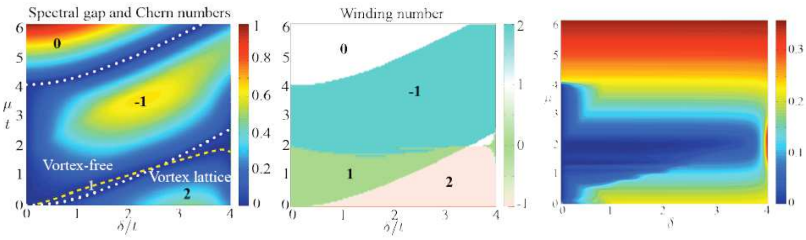
Ions interacting with lasers or magnetic field gradients can be used to implement a variety of strongly coupled spin-phonon models. The latter include cooperative Jahn-Teller or Rabi lattice models. By including the effect of optical phases on spin-phonon couplings, the system exhibits magnetic frustration as a result of the interplay between dressed spin-phonon couplings and long-range interactions. We predict a variety of interesting phenomena as a result of the large number of quasi-degenerate low-energy states, like the strong sensitivity of the system to external fields. Our results show that trapped ion systems are ideally suited to assess the efficiency of quantum annealing in finding the global ground state of frustrated Ising systems. Furthermore, we show that the sensitivity of spin-phonon systems close to a quantum phase transition can be used as the basis of a quantum metrological scheme for measuring external magnetic fields.

Measuring topology in complex systems

Emilio Alba

Instituto de Fisica Fundamental, CSIC, Serrano 113b, 28006, Madrid, Spain

Time-of-flight imaging is a powerful measurement tool for measuring topology in optical lattices [1]. In this talk we will analyze the information provided by these measurements in a model for topological superconductors (which is adiabatically connected to Kitaevs honeycomb model and signals the presence of Majorana modes [2]) and interacting Chern insulators, and find that entanglement and interactions affect time-of-flight observables in a distinct manner thus making them a resource for characterizing highly correlated systems.



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[1] E. Alba, X. Fernández-Gonzalvo, J. Mur-Petit, J.K. Pachos and J.J. Garcia-Ripoll, Phys. Rev. Lett. **107**, 235301 (2011).
[2] J.K. Pachos, E. Alba, V. Lahtinen and J.J. Garcia-Ripoll, Phys. Rev. A **88**, 013622 (2013).

Digital quantum simulation in superconducting circuits

A. Mezzacapo[a], U. Las Heras[a], J. Pedernales[a], L. Lamata[a], L. DiCarlo[b], S. Filipp[c], A. Wallraff[c], E. Solano[a,d]

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[d]IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain.

We propose the implementation of digital quantum simulators in superconducting architectures, by enhancing standard digital quantum simulation techniques with complex circuitQED quantum gates. We study the quantum simulation capability of a realistic superconducting setup, composed of transmon qubits and microwave resonators. We analyze the simulated dynamics for interacting spin models [1], and quantum Rabi and Dicke models [2]. By designing novel collective gates for superconducting qubits [3], we show that the dynamics of highly entangled fermionic systems can be recovered [4].

[1] U. Las Heras, A. Mezzacapo, L. Lamata, S. Filipp, A. Wallraff, E. Solano, Phys. Rev. Lett., in press, also e-print arXiv:1311.7626.
[2] A. Mezzacapo, U. Las Heras, J. Pedernales, L. DiCarlo, E. Solano, L. Lamata, in preparation.
[3] A. Mezzacapo, L. Lamata, S. Filipp, A. Wallraff, E. Solano, e-print arXiv:1403.3652.
[4] U. Las Heras, A. Mezzacapo, L. Lamata, E. Solano, in preparation.

Quantum Sensing with Trapped Ions

Jordi Mur-Petit

Instituto de Estructura de la Materia, IEM-CSIC, Serrano 123, 28006 Madrid, Spain

Formal developments in the context of quantum information theory, together with the superb experimental control on quantum systems attained in the last couple of decades, are giving rise to the appearance of a new field of research and development—quantum technologies—the use of quantum protocols and system to enhance available technology or even develop totally new devices [1]. Within this field, quantum metrology or quantum sensing focuses in establishing the measurement uncertainties achievable according to

quantum mechanics, to devise physical systems able to test them, and to design new measurement devices that translate these findings into practical applications [2]. Building on the exquisite control and precise detection methods available for trapped atomics ions [3], we have developed two proposals to use them as quantum probes of weak and/or short-pulsed electric fields. In our first proposal, we measure and stabilize the carrier-envelope-offset phase of a femtosecond frequency comb by multi-pulse quantum interferometry—a new interferometry protocol that uses a trapped ion as a nonlinear detector of the pulse-to-pulse phase variations of a fast train of laser pulses [4]. Our second work relies again on trapped ions, together with quantum logic and state-dependent forces, to determine the electric dipole moment of a polar molecule by measuring the extremely weak electric field that this produces on the nearby probe ion [5,6].

[1] J. P. Dowling, G. J. Milburn: "Quantum Technology: The Second Quantum Revolution", Phil. Trans. R. Soc. Lond. A **361**, 1655-1674 (2003).

[2] V. Giovanetti, S. Lloyd, L. Maccone: "Advances in Quantum Metrology", Nature Photon. **5**, 222-229 (2011).

[3] R. Blatt, D. J. Wineland: "Entangled states of trapped atomic ions", Nature **453**, 1008-1015 (2008); D. J. Wineland: "Nobel Lecture: Superposition, entanglement, and raising Schrödinger's cat", Rev. Mod. Phys. **85**, 1103 (2013).

[4] A. Cadarso, J. Mur-Petit, J. J. García-Ripoll: "Phase Stabilization of a Frequency Comb using Multipulse Quantum Interferometry", Phys. Rev. Lett. **112**, 073603 (2014).

[5] J. Mur-Petit, J. J. García-Ripoll: "Measurement and control of polar molecules using trapped atomic ions", e-print arXiv:1306.1416.

[6] J. Mur-Petit, J. J. García-Ripoll: "Collective modes of a trapped ion-dipole system", Appl. Phys. B **114**, 283-294 (2014), special issue "Wolfgang Paul 100".

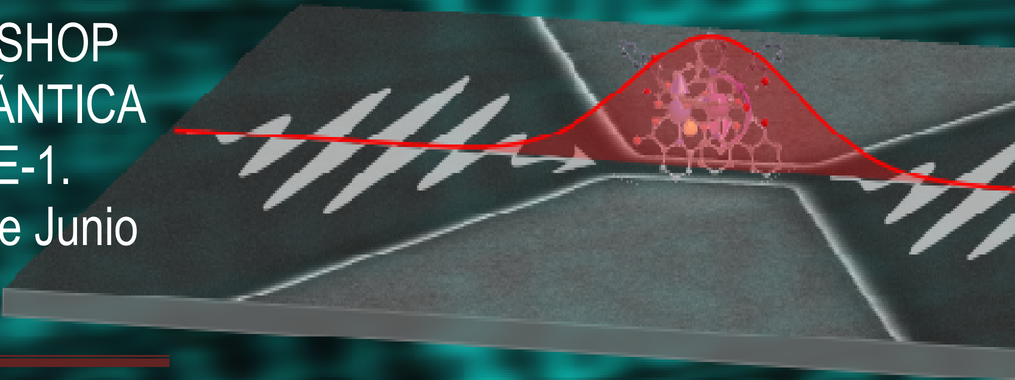
Entanglement Classification and Matrix Product States

(Invited)

Iñigo Luis Egusquiza

Universidad del País Vasco

We will give an arrangement of entanglement classes for symmetric states related to their Matrix Product State structure. In this manner we will assign physical significance to an entanglement classification.



Discording Power of Quantum Evolutions

Fernando Galve[1], Francesco Plastina[2,3], Matteo G. A. Paris[4,5], and Roberta Zambrini[1]

[1]FISC (UIB-CSIC), Instituto de Física Interdisciplinar y Sistemas Complejos, UIB Campus, E-07122 Palma de Mallorca, Spain
[2]Dipartimento di Fisica, Università della Calabria, I-87036 Arcavacata di Rende (Cosenza), Italy
[3]INFN—Gruppo collegato di Cosenza
[4]Dipartimento di Fisica dell'Università degli Studi di Milano, I-20133 Milano, Italy 5CNISM, UdR Milano Statale, I-20133 Milano, Italy

We introduce [1] the discording power of a unitary transformation, which assesses its capability to produce quantum discord, and analyze in detail the generation of discord by relevant classes of two-qubit gates. Our measure is based on the Cartan decomposition of two-qubit unitaries and on evaluating the maximum discord achievable by a unitary upon acting on classical-classical states at fixed purity. We find that there exist gates which are perfect discorders for any value of purity μ, and that they belong to a class of operators that includes the $\sqrt{\mathrm{SWAP}}$. Other gates, even those universal for quantum computation, do not possess the same property: the CNOT, for example, is a perfect discorder only for states with low or unit purity, but not for intermediate values. The discording power of a two-qubit unitary also provides a generalization of the corresponding measure defined for entanglement to any value of the purity.

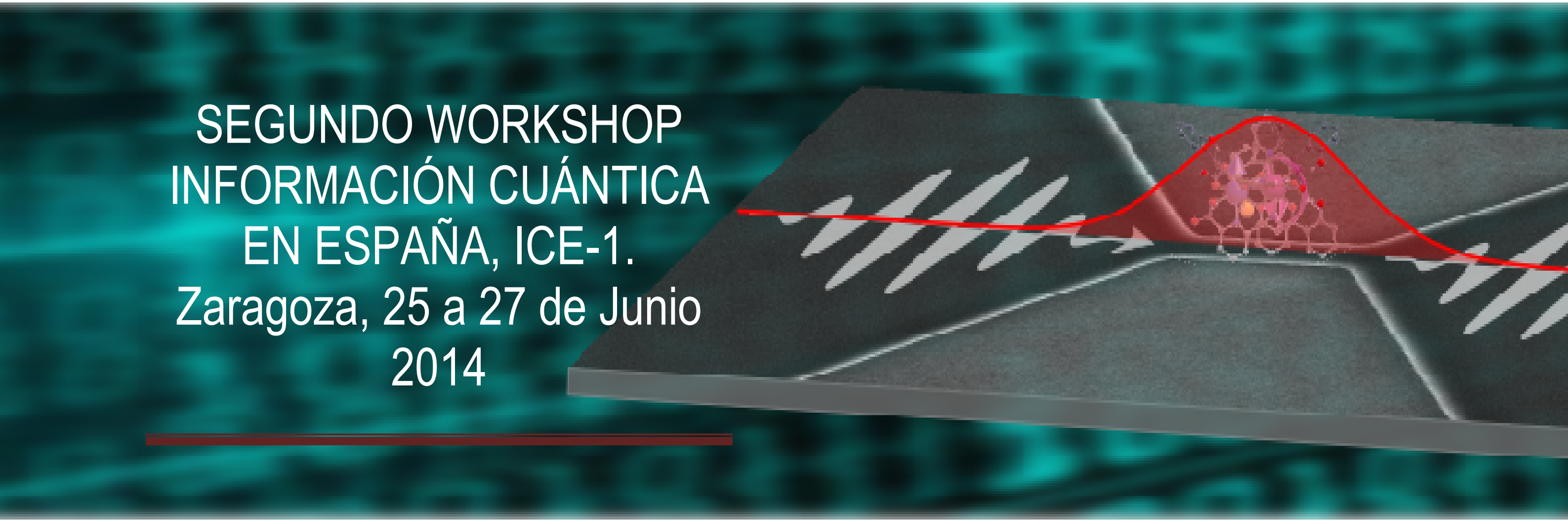
[1] Phys. Rev. Lett. **110**, 010501 (2013)

Detecting the nonlocality of many-body quantum states

Jordi Tura[1], Remigiusz Augusiak[1], Ana Belén Sainz[1], Tamás Vértesi[2], Maciej Lewenstein[1,3] and Antonio Acín[1,3]

[1]ICFO-Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain
[2]Institute for Nuclear Research, Hungarian Academy of Sciences, H-4001 Debrecen, P.O. Box 51, Hungary
[3]ICREA-Institució Catalana de Recerca i Estudis Avançats, Lluís Companys 23, 08010 Barcelona, Spain

One of the most important steps in the understanding of quantum many-body systems is due to the intensive studies of their entanglement properties. Much less, however, is known about the role of quantum nonlocality in these systems. This is because standard manybody observables involve correlations among few particles, while there is no multipartite Bell inequality for this scenario. Here [1] we provide the first example of nonlocality detection in many-body systems using only two-body correlations. To this aim,



we construct families of multipartite Bell inequalities that involve only second order correlations of local observables. We then provide examples of systems, relevant for nuclear and atomic physics, whose ground states violate our Bell inequalities for any number of constituents. Finally, we identify inequalities that can be tested by measuring collective spin components, opening the way to the experimental detection of many-body nonlocality, for instance with atomic ensembles.

[1] J. Tura *et al*, arXiv:1306.6860, accepted for publication in Science.

General limits for entanglement distribution

Alexander Streltsov

ICFO

Establishing quantum entanglement between two distant parties is an essential step of many protocols in quantum information processing. One possibility for providing long-distance entanglement is to create an entangled composite state within a lab and then physically send one subsystem to a distant lab. Moreover, recent results show that entanglement distribution is even possible by sending a disentangled particle. In this talk we provide general limits for the amount of entanglement which can be distributed between two distant parties. One such limit is given by quantum discord. We also discuss the scenario where the exchanged particle is disentangled, and show that states of rank two cannot be used for entanglement distribution in this case.

Spin-boson lattice models: Lieb-Robinson bounds, Ising phase transitions, and Luttinger liquids

(Invited)

Alejandro Bermúdez

Instituto de Física Fundamental, CSIC

In this talk, I will present our results on the study of hybrid lattice models composed spins and bosons interacting with each other. In particular, I will address three topics: (i) The possibility of deriving fundamental limits for the speed of propagation of spin-spin correlations (i.e. Lieb-Robinson bounds). (ii) The existence of a quantum phase transition in the Ising universality class that involves spins and boson on the same footing. (iii) The prospects of finding spin-boson instances of the Luttinger-liquid universality class. I will also discuss their connection to ion-trap and superconducting-circuit architectures.

Fermion-fermion scattering with superconducting circuits

L. García-Álvarez[a], J. Casanova[a], A. Mezzacapo[a], I. L. Egusquiza[b], L. Lamata[a], G. Romero[a], and E. Solano[a,c]

[a] Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain
[b] Department of Theoretical Physics and History of Science, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain
[c] IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain

We propose a digital-analog quantum simulation of fermion-fermion scattering in the context of quantum field theories (QFTs) with superconducting circuits [1]. This quantum technology provides strong coupling between superconducting qubits with a microwave resonator, and a continuum of bosonic modes, which in turn allows us to implement a discrete set of fermionic modes interacting with the bosonic *continuum*. This effort may represent a significant advance towards full-fledged quantum simulation of QFTs in a controllable system.

[1] L. García-Álvarez, J. Casanova, A. Mezzacapo, I. L. Egusquiza, L. Lamata, G. Romero, and E. Solano, arXiv:1404.2868 (2014).

Spectral origin of non-Markovianity in an exact finite harmonic model

Ruggero Vasile, Fernando Galve, Roberta Zambrini

IFISC (UIB-CSIC), Instituto de Física Interdisciplinar y Sistemas Complejos, Palma de Mallorca, Spain

Open systems in the quantum formalism are described through an elegant theoretical approach leading to master or to Langevin equations. A fundamental assumption in phenomenological approaches is the form of the spectral density J(ω) embedding all information about the real couplings and frequencies in the complex infinite environment, and the structure of the coupling to the system. Typical approximations to simplify the treatment, such as negligible memory effects (Markovian approximation), system time coarse graining, weak system-bath coupling, large frequency cut-off, Ohmic spectral density, drastically constrain the possible frequency dependence of J(ω). Important deviations from these simple instances, however, are common in several systems and can lead to memory effects and deviations from Markovian dynamics. These effects can be quantified with several measures and recently different approaches have been proposed focusing on deviations from the Lindblad form of the generator of the master equation [1], on flow-back of information from the environment [2], or on entanglement decay with an ancilla [3], to mention some of them. In this talk we identify non-Markovian effects originating in the structure of the system and bath couplings as well as in the distribution of energies considering a microscopic model given by an inhomogeneous harmonic chain, avoiding the limitations of approximate approaches. The case of an oscillator attached to a homogeneous chain was already studied by Rubin to determine the statistical properties of crystals with defects: this configuration leads to a Ohmic dissipation (thus Markovian, at least for large temperature) [4]. Here we will discuss the potential offered by non-homogeneous tunable chains. As a matter of fact, experimental implementation of a tunable chain of oscillators can be obtained through recent progress in segmented Paul traps [5, 6] also allowing tunability of ions couplings and on-site potentials. Other possible setups are based on photonic crystal nanocavities, microtoroid resonators or optomechanic resonators [7]. Furthermore, correlations spectra of the system can be measured to gain insight on the spectral density induced by the rest of the chain [8, 9]. The non-homogeneous harmonic chain we consider in this work represents then a structured and controllable reservoir amenable to experimental realization. Moving to non-homogeneous chain configurations [10] allow us to inquire the origin of non-Markovianity and to distinguish among several independent features quantifying separately different sources of non-Markovian dynamics. When focusing on periodic systems (e.g. dimers), we can engineer spectral densities with finite band-gaps, like in semiconductors or photonic crystals. For suitable couplings we show that the system is actually influenced by the resonant portion of the environment. Memory effects are then evaluated by sweeping the spectral density for a structured bath allowing us to show the effects of the local form of the spectrum. Non-Markovianity is quantified with the mentioned measures of information flow-back and non-divisibility of the system dynamical map [2, 3]. We show strongest memory effect at band-gap edges and provide an interpretation based on energy flow between system and environment. A system weakly coupled to a stiff chain ensures a Markovian dynamics, while the size of the environment as well as the local density of modes are not substantial factors. We show an opposite effect when increasing the temperature inside or outside the spectral band-gap. Further, non-Markovianity arises for larger (negative and positive) powers of algebraic spectral densities, being the Ohmic case not always the most Markovian one. Ongoing developments of this research project will be also presented.

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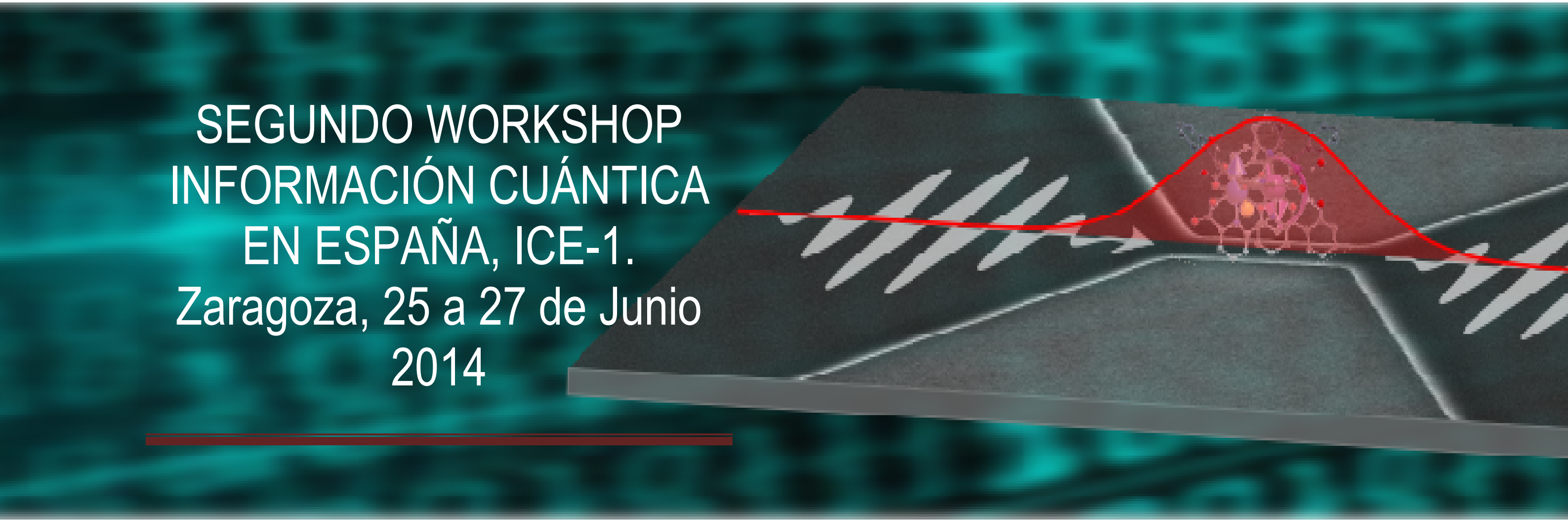
[2] H.-P. Breuer, E.-M. Laine, and J. Piilo, Phys. Rev. Lett. 103, 210401 (2009).
[3] A. Rivas, S. F. Huelga, and M. B. Plenio, Phys. Rev. Lett. 105, 050403 (2010).
[4] R. J. Rubin , Phys. Rev. 131, 964 (1963), and references therein.
[5] A. Walther et al., Phys. Rev. Lett. 109, 080501 (2012).
[6] R. Bowler et al., Phys. Rev. Lett. 109, 080502 (2012).
[7] M. Aspelmeyer, S. Groeblacher, K. Hammerer, and N. Kiesel, J. Opt. Soc. Am. B 27, 189 (2010).
[8] S. Groeblacher, A. Trubarov, N. Prigge, M. Aspelmeyer and J. Eisert, arXiv:1305.6942 (2013).
[9] W.M. Zhang, P. Y. Lo, H. N. Xiong, M. W. Y. Tu; F.Nori Phys. Rev. Lett. 109, 170402 (2012).
[10] R. Vasile, F. Galve, R. Zambrini, Phys. Rev. A 89, 022109 (2014).



Thursday, June the 26th 2014
Aula Magna, Edificio Paraninfo

Primes go Quantum

(Invited)

Germán Sierra

Instituto de Física Teórica

Prime numbers are the building blocks of Arithmetics and therefore classical objects. However, they can be treated as quantum objects by superposing them in the computational basis of a quantum computer. In this talk we shall apply quantum information tools to create the Prime state, and to quantify its entanglement properties in terms of number theoretical functions.

Entanglement, tensor networks and black hole horizons

Javier Molina-Vilaplana

Universidad Politécnica de Cartagena

We investigate a recent conjecture connecting the AdS/CFT correspondence and entanglement renormalization tensor network states (MERA). The proposal interprets the tensor connectivity of the MERA states associated to quantum many body systems at criticality, in terms of a dual holographic geometry which accounts for the qualitative aspects of the entanglement and the correlations in these systems. In this work, we propose a simple MERA tensor network to describe quantum critical systems at finite temperature. In the AdS/CFT, the gravity dual of a finite temperature state is the well-known AdS black hole in which the inverse temperature of the system is related with the distance of the boundary CFT to the black hole horizon. It has been argued that, inspired by the thermofield double construction of the eternal black hole, a MERA network with an horizon may be described by doubling the standard MERA for a pure state and then connecting together the infrared regions of both networks through a gluing-through-entanglement (GTE) operation. We show that the GTE operation may be satisfactorily characterized in terms of Matrix Product Density Operators (MPDO) and their purificatons.

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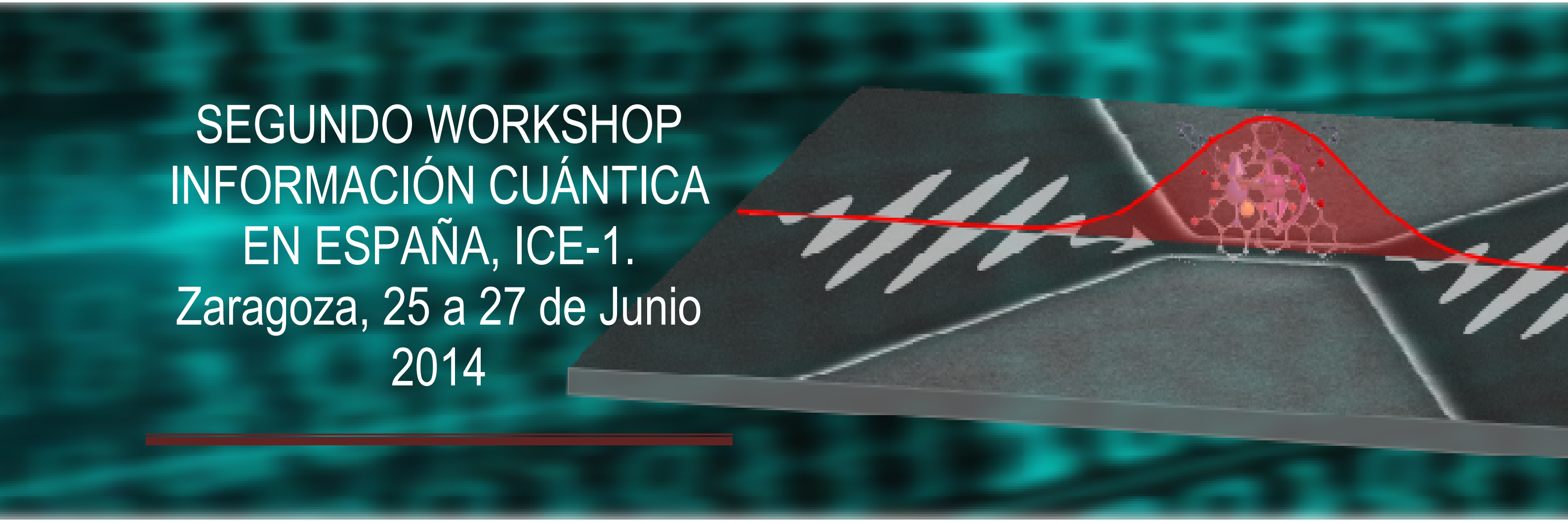

Thermodynamics Cost of Creating Correlations

Marcus Huber[a,b], Martí Perarnau-LLobet[b], Karen V. Hovhannisyan[b], Paul Skrzypczykb, Claude Klöckla, Nicolas Brunnerc, and Antonio Acín[b,d]

[a]Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
[b]ICFO-Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
[c]Département de Physique Théorique, Université de Genève, 1211 Genève, Switzerland
[d]ICREA-Institució Catalana de Recerca i Estudis Avançats, Lluis Companys 23, 08010 Barcelona, Spain

We investigate the fundamental limitations imposed by thermodynamics for creating correlations. Considering a collection of initially uncorrelated thermal quantum systems, we ask how much classical and quantum correlations can be obtained via a cyclic Hamiltonian process. We derive bounds on both the mutual information and entanglement of formation, as a function of the temperature of the systems and the available energy; and we discuss explicit protocols that can saturate such bounds. We also characterize the maximal temperature that allows for the creation of entanglement. In the multipartite case, we consider several types of entanglement, in particular genuine multipartite and bipartite entanglement. We find an (almost) linear scaling between the number of subsystems and the maximal temperature required to generate (multipartite) entanglement. That is, both bipartite and genuine multipartite entanglement can be created at arbitrary high temperatures if we have enough copies of the system. This approach may find applications, e.g. in quantum information processing, for physical platforms in which thermodynamical considerations cannot be ignored. This work is based on [1], and it is embedded on the recent interest on finding connections between quantum information and thermodynamics (see, for example, [2-4]).

[1] arXiv:1404.2169[quant-ph] (2014).
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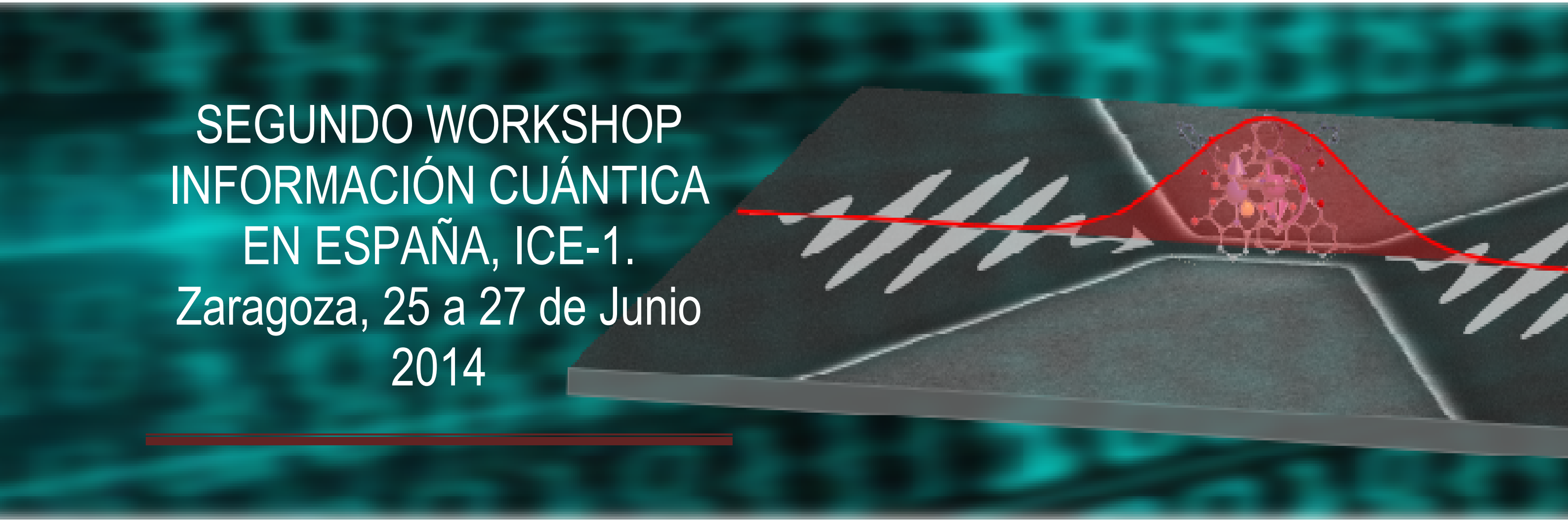

Classical microwaves as a universal model system for quantum contextuality

D. Frustaglia[a], J.P. Baltanás[a], M.C. Velázquez[b], A. Fernández[b], V. Losada[b], M. Freire[b], and A. Cabello[a]

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[b]Departamento de Electrónica y Electromagnetismo, Universidad de Sevilla, Spain.

Contextuality, a far-reaching generalization of nonlocality, stands out as a necessary resource for fault-tolerant quantum computation and other quantum-information tasks. Still, contextuality itself is not a signature of quantumness, since it can be simulated by classical models at the cost of extra memory. So far, these models are created ad hoc for each contextuality proof. This raises the question of whether quantum contextuality can be universally simulated with classical systems. Here we show [1] that classical electromagnetic waves provide a universal model for quantum contextuality in experiments with sequential measurements in which intermediate outcomes are stored in extra degrees of freedom. We support this by presenting experimental evidence of the state-independent violation of the Peres-Mermin noncontextuality inequality and the state-dependent violation of the noncontextuality version of Mermin's inequality with classical microwaves at the frequency used in consumer ovens. This is based upon the detection of intensity correlations under the assumption that intensities are ultimately due to a succession of individual events. Our results coincide with those found in quantum tests with ions, photons and neutrons. Unlike ad hoc classical contextual models, classical electromagnetism emerges as a universal model revealing the precise location of the memory needed to generate contextual outcomes and the mechanism to do it: the relative phase of the electromagnetic field in the extra degrees of freedom storing the intermediate outcomes. The principles explaining the bounded nature of contextuality and nonlocality in quantum theory are then tied to the question of why classical electromagnetism, under proper tests, is equally bounded.

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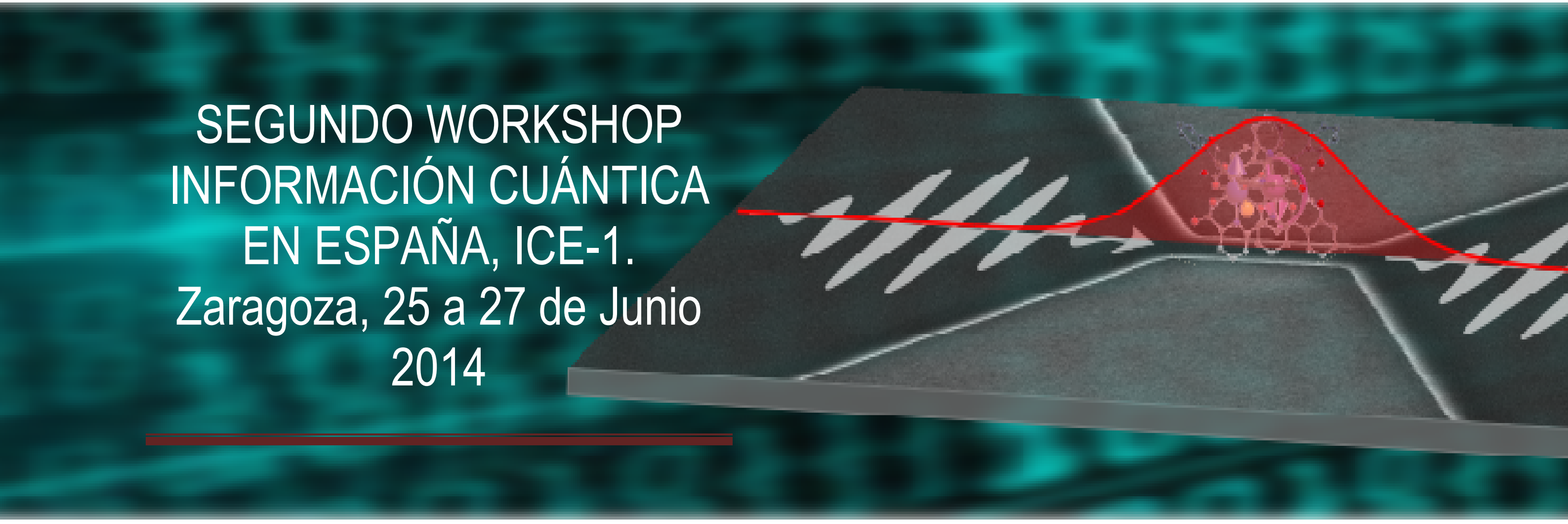

Sampling quantum non-local correlations with high probability

C. E. González-Guillén[a,b], C. H. Jiménez[c], C. Palazuelos[c,d] and I. Villanueva[b,c]

[a]*Universidad Politécnica de Madrid*
[b]*Instituto de Matemática Interdisciplinar, U.C.M.*
[c]*Universidad Complutense de Madrid*
[d]*Instituto de Ciencias Matemáticas, Madrid*

It is well known that two spatially separated observers, sharing an entangled quantum state and performing appropriate measurements, can produce some correlations which cannot be explained by a local hidden variable model. These quantum nonlocal correlations are a crucial resource in many applications like quantum cryptography, random number generators and communication protocols. In this work we study how to naturally sample quantum nonlocal correlations with high probability.

Embedding Quantum Simulators

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[b]*Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado 1761, Peru*
[c]*IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain*

We introduce the concept of embedding quantum simulators, a paradigm allowing efficient computation of dynamical quantities requiring full quantum tomography in a standard quantum simulator (one-to-one quantum simulator). The concept consists in the suitable encoding of a simulated quantum dynamics in the enlarged Hilbert space of an embedding quantum simulator. In this manner, non-trivial quantities are mapped onto physical observables, overcoming the necessity of full tomography, and reducing drastically the experimental requirements. As examples, we discuss how to evaluate entanglement monotones and time correlation functions, each in a suitable embedding quantum simulator. Finally, we expect that the proposed embedding framework paves the way for a general theory of enhanced one-to-one quantum simulators.

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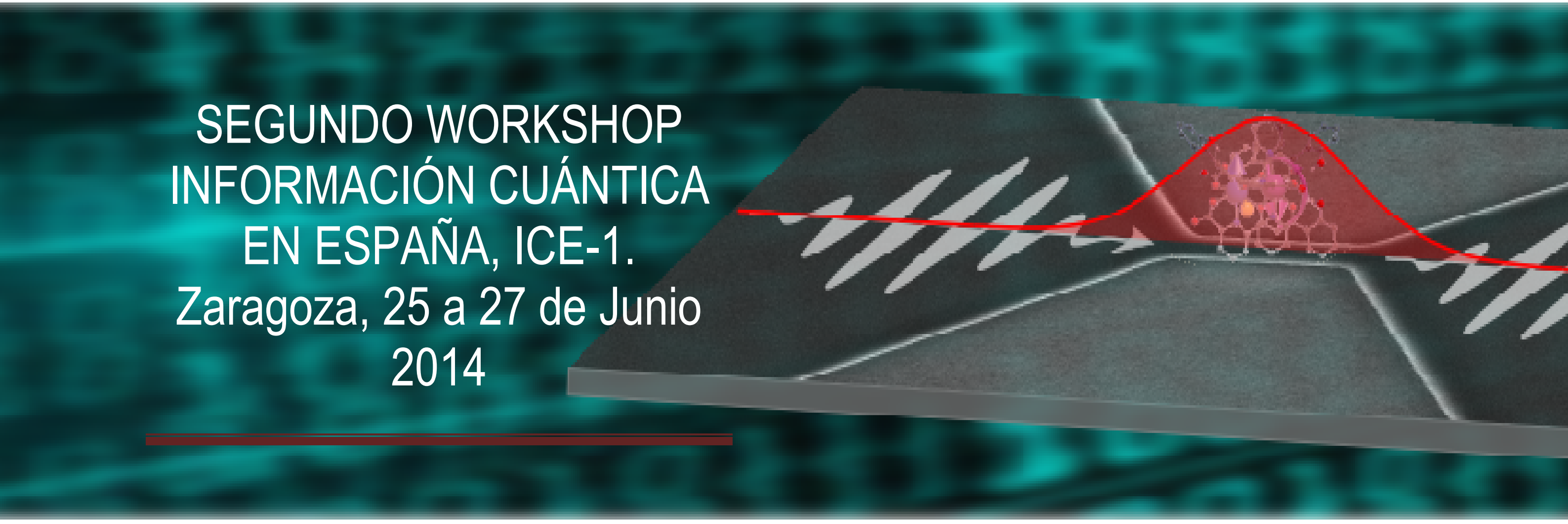


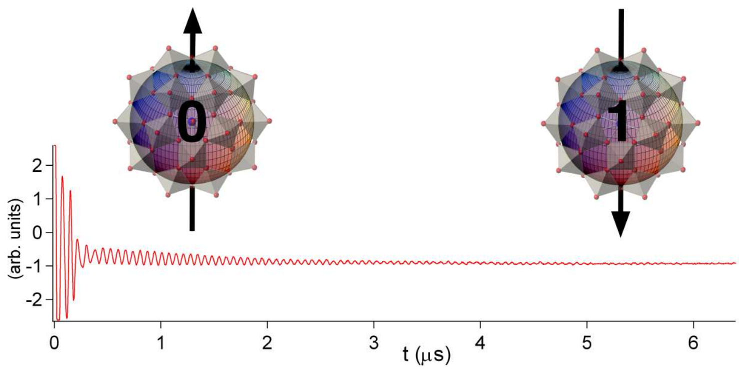
Design of molecular spin qubits based on polyoxometalates

(Invited)

<u>Eugenio Coronado</u>, José Jaime Baldoví, Alejandro Gaita, Helena Prima

Instituto de Ciencia Molecular (ICMol), Universidad de Valencia

Chemistry provides nice examples of molecular nanomagnets showing quantum effects in the solid state. Still, a great challenge is the manipulation of the spins in these molecules for a sufficiently long time. In terms of quantum computing, this means the preservation of quantum coherence, i.e. all the information on the wave function, during the application of many quantum gate operations. This is a daunting task, but fortunately chemistry can provide the basics for the rational design and optimization of the building blocks with the aimed quantum behavior. Among these molecular building blocks, magnetic polyoxometalates (POMs) combine a rich magnetochemistry with an arbitrarily low abundance of nuclear spins [1]. Here we will show that in these molecular metal oxides a high coherence can be achieved by chemically and structurally minimizing the sources of decoherence [2,3]. We will show the excellent potential of these molecules not only for the storage of quantum information but even for the realization of quantum algorithms [4].



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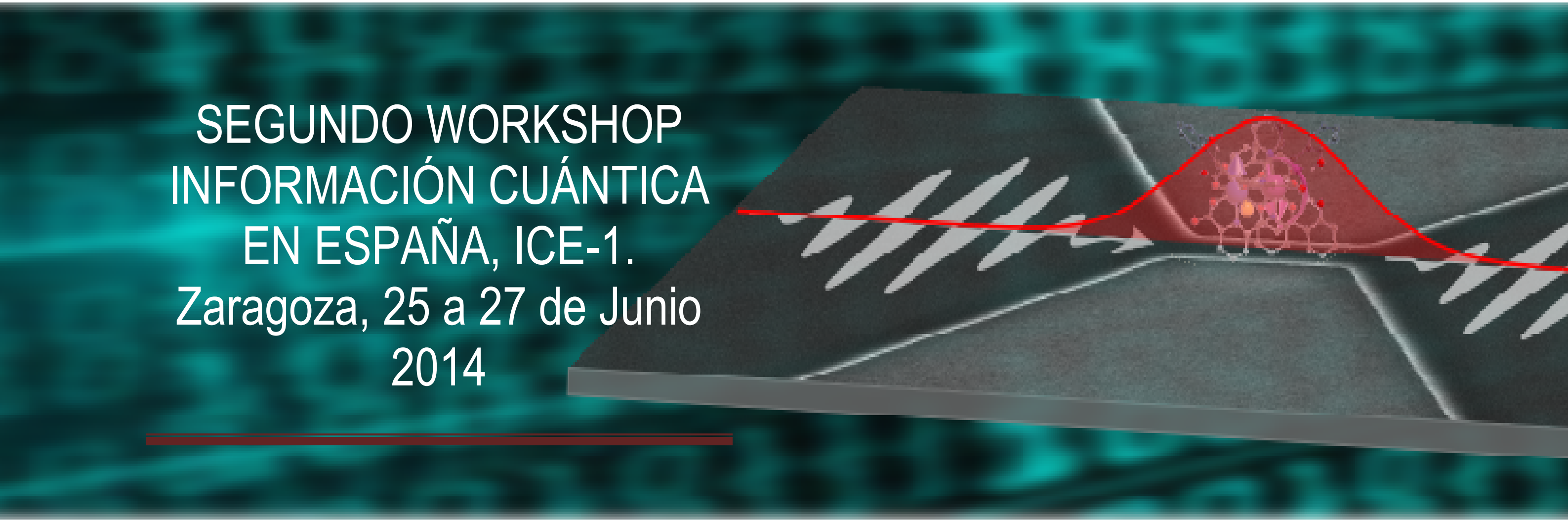

Dinuclear Molecules of Lanthanides as Prototypes of CNOT and SWAP Quantum Gates

G. Aromí[a], D. Aguilà[a], L. A. Barrios[a], V. Velasco[a], S. J. Teat[c], F. Luis[b], O. Roubeau[b], A. Repollés[b], J. P. Alonso[b]

[a] *Departament de Química Inorgànica, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.*
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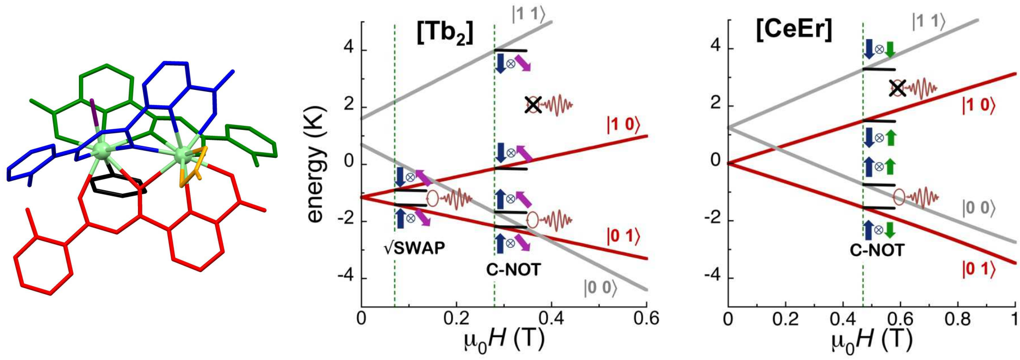
The manipulation of the quantum states of electronic spins has been proposed as a possible technology for the realization of the principles of quantum computing.[1] The spins can be confined in various forms of matter, but one that seems convenient is within metals of discrete coordination molecules,[2-4] which can then be processed or localized conveniently, prepared in any desired amount with complete reproducibility and have their properties tuned by chemical synthesis. Here we discuss the synthesis of a family of dissymmetric dinuclear coordination complexes, [Ln_2], (Ln=any lanthanide, Figure, left)[5] that fulfill many of the requirements necessary to act as CNOT or SWAP quantum gates.[6] The synthetic method also allows for the controlled preparation of a large number of heterometallic analogues, [LnLn']. This provides the possibility to study any of the two individual qubits within the complex by having it be accompanied by a diamagnetic metal at the place of the other qubit (eg, [LaLn'] or [LnY]) or to explore other implementation schemes through the preparation and study of different combinations (such as [CeEr]). The physical properties proving the suitability of these chemical systems to embody 2-qubit quantum gates will be discussed (Figure right).



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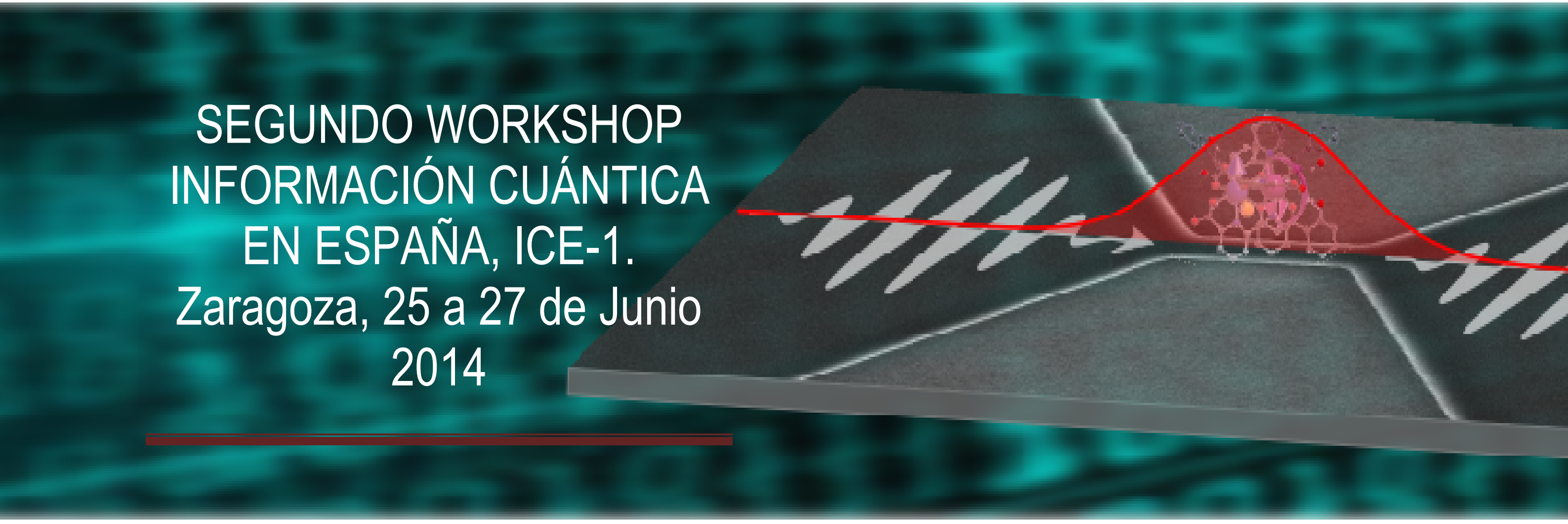

A molecular approach to spin qubits: decoherence and organisation in Single-Ion-Magnets

A. Gaita-Ariño, J. J. Baldoví, L. Escalera-Moreno, H. Prima-García, G. Mínguez-Espallargás, J. M. Clemente-Juan and E. Coronado

Universitat de València, ICMol, Spain

Magnetic molecules based on rare earth ions are promising hardware to perform theoretical and experimental studies with the final goal of achieving coherent spin control. In this context, we employ as theoretical tools the home-made programs MAGPACK and SIMPRE.[1] Experimentally, we rely mostly on magnetometry for characterization -complemented when available by spectroscopic techniques- and pulsed-Electronic Paramagntic Resonance for the coherent manipulation. In a recent experimental study, it was possible to increase the number of coherent rotations tenfold through matching the Rabi frequency with the frequency of the proton for the polyoxometalate single ion magnet $[GdW_{30}P_5O_{110}]^{14-}$.[2] We have been recently able to understand the magnetic anisotropy of lanthanoid complexes using an effective point-charge model.[3] Building upon this understanding, we are now proposing a new setup for the electrical control of spin qubits embodied by mononuclear lanthanide complexes, via the change in the extradiagonal parameters of the crystal field Hamiltonian. We rationalize the expected results with the help of *ab initio* calculations and an effective point charge model. We also propose a Quantum Error Correction experiment inspired by the Shor code using a trinuclear lanthanide complex in an ENDOR setup. We detail how the combined electron-nuclear spin manifold in this system can be thought of as equivalent to the 9 qubits as required by Shor's code. Finally, we recently achieved the spatially regular organisation of three different spin qubits, reminiscent of Lloyd's “global control” scheme for quantum computing.[4]

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[2] J. J. Baldoví, S. Cardona-Serra, J. M. Clemente-Juan, E. Coronado, A. Gaita-Ariño and H. Prima,, *Chem. Comm.,* **2013**, 49, 8922- 8924, arxiv:1308.5839

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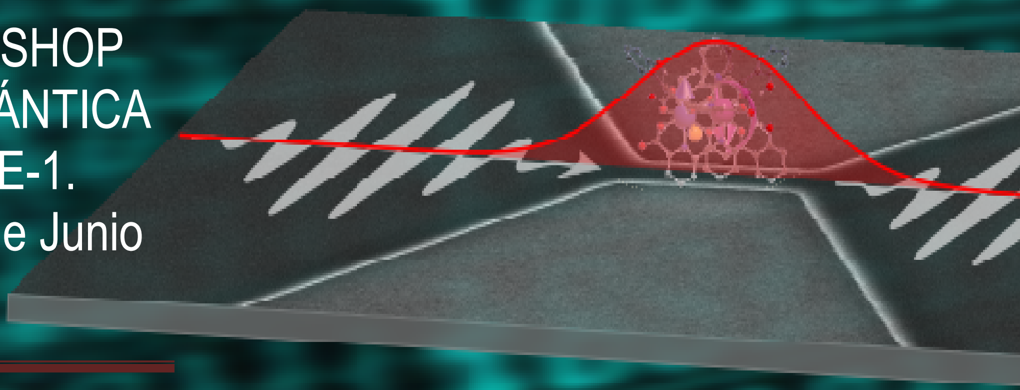


Mathematical and physical meaning of the Bell inequalities

(Invited, 50 years of Bell's inequalities)

Emilio Santos Corchero

Universidad de Cantabria

It is shown that the Bell inequalities are closely related to the triangle inequalities involving distance functions amongst pairs of random variables with values {0,1}. A hidden variables model is defined as a mapping between a set of quantum projectors and a set of random variables. The model is noncontextual if there is a joint probability distribution. The Bell inequalities are necessary conditions for its existence. The inequalities are most relevant when measurements are performed at space-like separation, a possibility showing a conflict between quantum mechanics and local realism (Bell´s theorem).

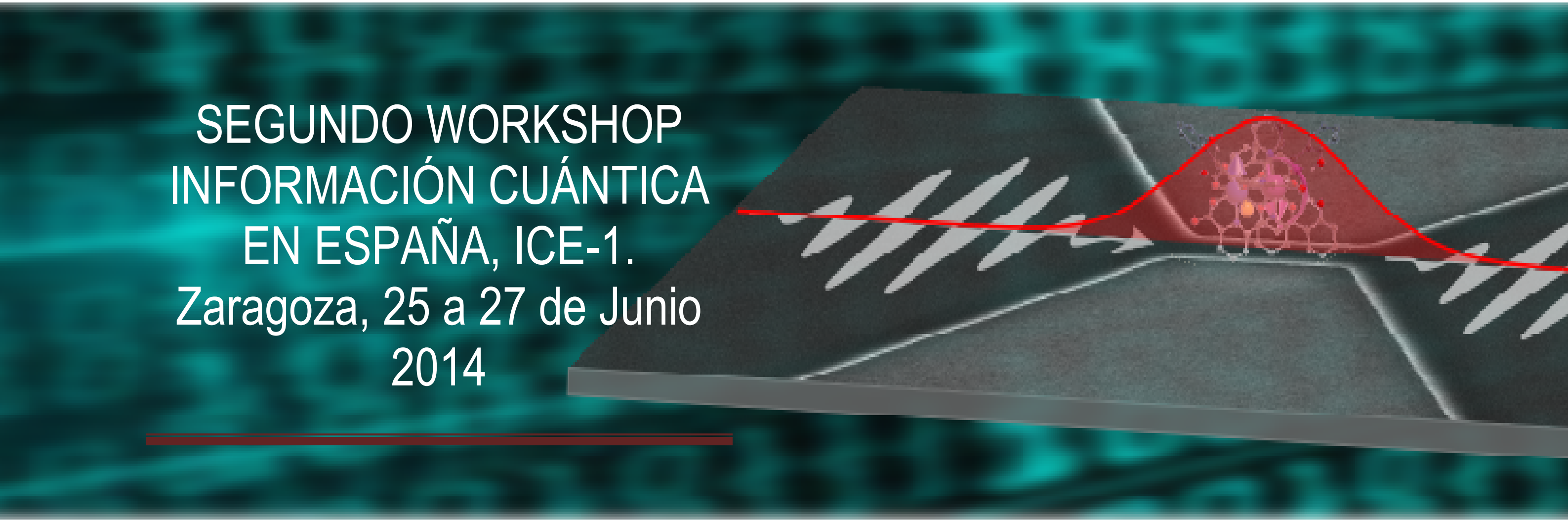
John Bell and the right question

(Invited, 50 years of Bell's inequalities)

Adan Cabello

Universidad de Sevilla

Bell will be remembered for being the first who realize that, in quantum theory, correlations between outcomes of jointly measurable observables violate certain inequalities satisfied by local (and noncontextual) hidden variables theories. Then, Tsirelson has to be remembered as the first who realize that violations of Bell inequalities are themselves upper bounded in nature. Similarly, Popescu and Rohrlich have to be remembered for being the first ones who asked the "right" question: Why? What reasons or physical principles enforce the violation of Bell inequalities up, but not beyond, certain limits? We will report some recent results related to this question. Specifically, we will identify which Bell and noncontextuality inequalities are violated in nature, which violations are possible and which principle explains that higher violations cannot occur.



Imaginación Cuántica

(Invited, open session)

José Ignacio Latorre

Universidad de Barcelona

La Mecánica Cuántica establece los límites de nuestro conocimiento sobre la Naturaleza, devolviendo una buena dosis de humildad a la especie humana. A la par, la Mecánica Cuántica nos ha permitido desarrollar instrumentos increíblemente útiles que empleamos, por ejemplo, en medicina, informática, comunicaciones e incluso para crear relojes ultraprecisos. La Mecánica Cuántica requiere imaginación, tanto para comprenderla, como para adivinar cómo alterará nuestras vidas en un futuro próximo.

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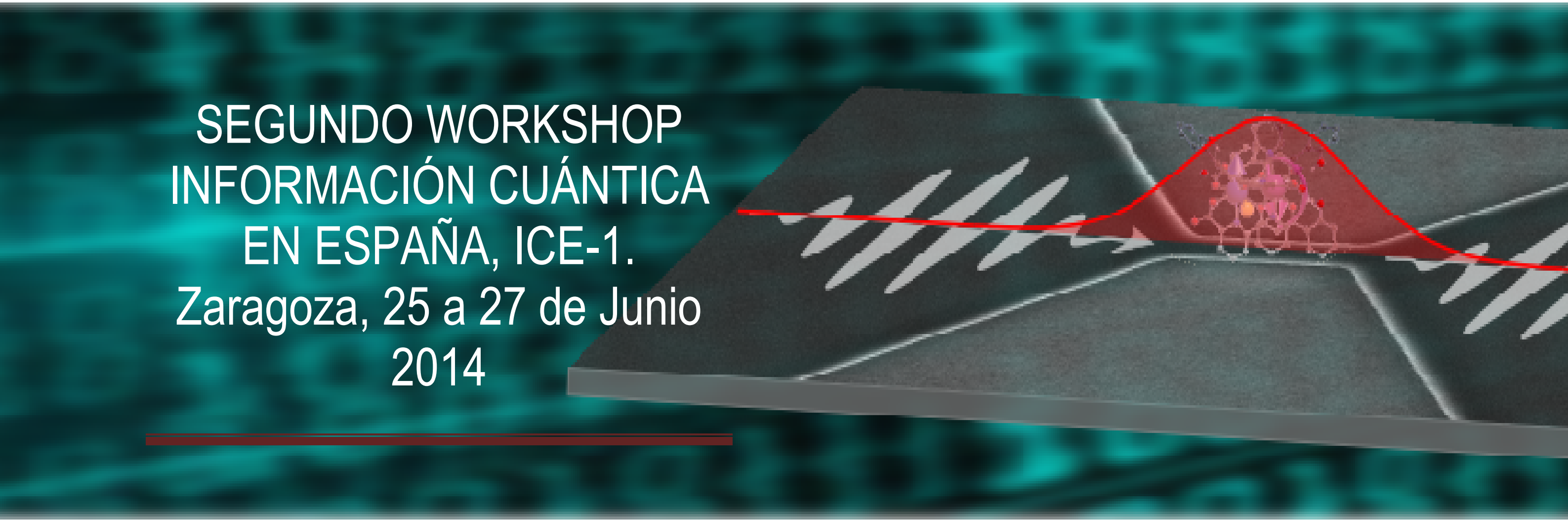

Friday, June the 27th 2014
Sala de grados, Facultad de Ciencias (A)

Bulk-boundary theories from a quantum information theory perspective

(Invited)

Ignacio Cirac

Max-Planck-Institut für Quantenoptik

Tensor networks states describe many-body quantum systems with local interactions in thermal equilibrium. At zero temperature, they correspond to ground states of frustration-free local Hamiltonians, and fulfill the so-called area law: the entropy of the reduced state corresponding to a connected region scales with the area surronding that region, and not with its volume. This indicates that there should be a holographic map between the bulk and the boundary of any connected region. We derive such a map, and show how the bulk properties of the state can be obtained from a theory that lives at the boundary, described by a boundary Hamiltonian. For gapped systems, that Hamiltonian is local and becomes non-local as one approaches a gapless phase. For topological phases, the Hamiltonian can be splitted into a universal one, which is constant in the whole phase, and a local Hamiltonian which depends on the microscopic details.

Quantum and classical simulations of emergent phenomena in one dimensional quantum field theories

Fernando Quijandría[1], Diego Blas[2], Oriol Pujolàs[3], David Zueco[1,4]

[1]Instituto de Ciencia de Materiales de Aragón y Departamento de Física de la Materia Condensada, CSIC-Universidad de Zaragoza, Zaragoza E-50012, Spain
[2]CERN, Theory Division, 1211 Geneva, Switzerland
[3]Departament de Física and IFAE, Universitat Autònoma de Barcelona, Bellatera 08193, Barcelona, Spain
[4]Fundacion ARAID, Paseo María Agustín 36, Zaragoza 50004, Spain

Consider two quantum fields in one dimension (relativistic and non-relativistic). We show that, despite each of them exhibits a different group velocity in the high-energy regime, Lorentz invariance emerges as a symmetry of the system at long wavelengths. We start with a theoretical approach of the problem. Second order perturbation theory and renormalization group techniques are used to analyze the running of the velocities with the energy scale. As the strong coupling regime becomes intractable using the standard tools of QFT, we move to a classical (numerical) simulation of the non-relativistic case. The latter is based in bosonization techniques and the continuous matrix product states formalism. Finally, we propose a quantum simulation for the relativistic case using superconducting circuits. Here the problem is modeled using transmission lines coupled non-linearly by means of Josephson junctions.

Efficient method to measure n-time correlation functions

J. S. Pedernales[a], R. Di Candia[a], I. L Egusquiza[b], J. Casanova[a], and E. Solano[a,c]

[a]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain
[b]Department of Theoretical Physics and History of Science, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain
[c]IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain

Ranging from the linear response theory to quantum field theories, time correlation functions are omnipresent in physics and are considered a key magnitude for a complete description of nature. The measurement of time correlation functions of classical observables does not represent an especially difficult task, as it is just the product of the outcomes of two measurements performed at two different times. However, time correlations of quantum mechanical observables happen to be a demanding magnitude to extract. This is because a measurement at time t1 causes the collapse of the wave function, perturbing the outcome of any further measurement. In this talk we will present a method that provides efficient access to n-time correlation functions using an ancillary qubit [1]. We will also discuss a possible implementation of the method in trapped ions [2] and its applicability in the framework of the linear response theory, where one can measure magnitudes as the electric or magnetic susceptibilities in terms of time correlation functions. Finally, we will talk about the suitability of our method to the measurement of Leggett-Garg inequalities, a.k.a. temporal Bell inequalities, where the time correlation functions are used to unwrap the quantum character of nature.

[1] J. S. Pedernales, R. Di Candia, I. L. Egusquiza, J. Casanova, and E. Solano, arXiv:1401.2430
[2] J. S. Pedernales, J. Casanova, J. Home, and E. Solano, in preparation

Entanglement detection in coupled particle plasmons

Javier del Pino,[1,2] Johannes Feist,[1] F.J. García-Vidal,[1] and Juan José García-Ripoll[2]

[1]Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, Madrid E-28049, Spain
[2]Instituto de Física Fundamental, IFF-CSIC, Calle Serrano 113b, Madrid E-28006, Spain

When in close contact, plasmonic resonances interact and become strongly correlated. We develop a quantum mechanical model for an array of coupled particle plasmons. This model predicts that when the coupling strength between plasmons approaches or surpasses the local dissipation, a sizable amount of entanglement is stored in the collective modes of the array. We also prove that entanglement manifests itself in far-field images of the plasmonic modes, through the statistics of the quadratures of the field, in what constitutes a novel family of entanglement witnesses. Finally, we estimate the amount of entanglement, the coupling strength and the correlation properties for a system that consists of two or more coupled nanospheres of silver, showing evidence that our predictions could be tested using present-day state-of-the-art technology.

Few Photon Photonics in One-Dimensional systems

(Invited)

Luis Martín-Moreno

Instituto de Ciencia de Materiales de Aragón

Light-matter interaction is one of the most fascinating topics in physics. Its enhancement using few-level-systems (FLS) in cavities has lead to the rich field of Cavity Quantum Electrodynamics. More recently, it has been realized that enhanced light-matter interaction can be realized in quasi-one-dimensional waveguides, such as dielectric waveguides, superconducting strips, photonic crystal waveguides, plasmonic waveguides, etc. Different types of waveguides may work at different frequency ranges and different physical conditions (like temperature), but they all profit from the confinement of the field and the reduced dimensionality in light propagation. Several results are known in these one-dimensional quantum-electrodynamics systems, but the large majority of them have been obtained considering one incoming photon, and within the rotating-wave-approximation, valid for small couplings between the photon field and the FLS, which conserves the total number of excitations (be it a photon or an excitation of the FLS). New effects, and perhaps strong photon-photon interaction mediated by the FLS, are expected when a few photons are launched into the waveguide. However, the theoretical analysis is this many-body situation is notoriously difficult and has only been performed for a few cases concerning two and three photons treated with simplified hamiltonians (as linear photonic dispersion relations in the waveguides and rotating wave approximation). In this talk we will present a general framework that can address the full many-body situation where any number of photons in a waveguide interact with an arbitrary number of FLS. Our formalism can take into account both the intricacies of non-linear dispersion relations (and thus the existence of band edges) and the full FLS-field hamiltonian (including the counter-rotating terms that do not conserve the number of excitations). We will present results for the few-level dynamics, transmission and resonant fluorescence as a function of FLS-field coupling, including the so-called ultrastrong coupling regime.

Superconducting Vortex Lattice for Ultracold Atoms

(Invited)

Oriol Romero-Isart

Institute for Quantum Optics and Quantum Information

In this talk I will propose and analyze a nanoengineered vortex array in a thin-film type-II superconductor as a magnetic lattice for ultracold atoms. This proposal addresses several of the key questions in the development of atomic quantum simulators. By trapping atoms close to the surface, tools of nanofabrication and structuring of lattices on the scale of few tens of nanometers become available with a corresponding benefit in energy scales and temperature requirements. This can be combined with the possibility of magnetic single site addressing and manipulation together with a favorable scaling of superconducting surface-induced decoherence.

Coupling superconducting circuits to single molecular magnets

Mark David Jenkins Sánchez

Instituto de Ciencia de Materiales de Aragón, CSIC- Universidad de Zaragoza

Superconducting coplanar waveguides and resonators are promising candidates for the realization of realistic quantum computing architectures. These devices are the basis of what has become known as circuit quantum electrodynamics (CQED) and allow for the coupling of microwave radiation to different quantum systems in a strong coupling regime [1]. We study the coupling properties of single molecular magnet qubits from the LnW_{30} family [2] to this type of circuits and find limits on the strong coupling regime in this case [3]. In order to achieve strong coupling to these qubits we have designed, fabricated and tested nanometer wide constrictions in the centerline of coplanar waveguide resonators. We find that the resonator properties are conserved while allowing us to increase the field in the vicinity of the constriction possibly allowing us to achieve strong coupling to small ensembles of qubits in the near future.

[1] R. J. Schoelkopf and S. M. Girvin, *Nature* ***451**,* 664-669 (2008)
[2] S. Cardona-Serra et al., *J. Am. Chem. Soc.* **134** (36), 14982–14990 (2012)
[3] Mark Jenkins et al., *New J. Phys.* **15** 095007 (2013)

Quantum Biomimetics and the Cloning of Quantum Observables

M. Sanz[a], U. Alvarez-Rodriguez[a], P. Pfeiffer[a], L. Lamata[a], E. Solano[a,b]

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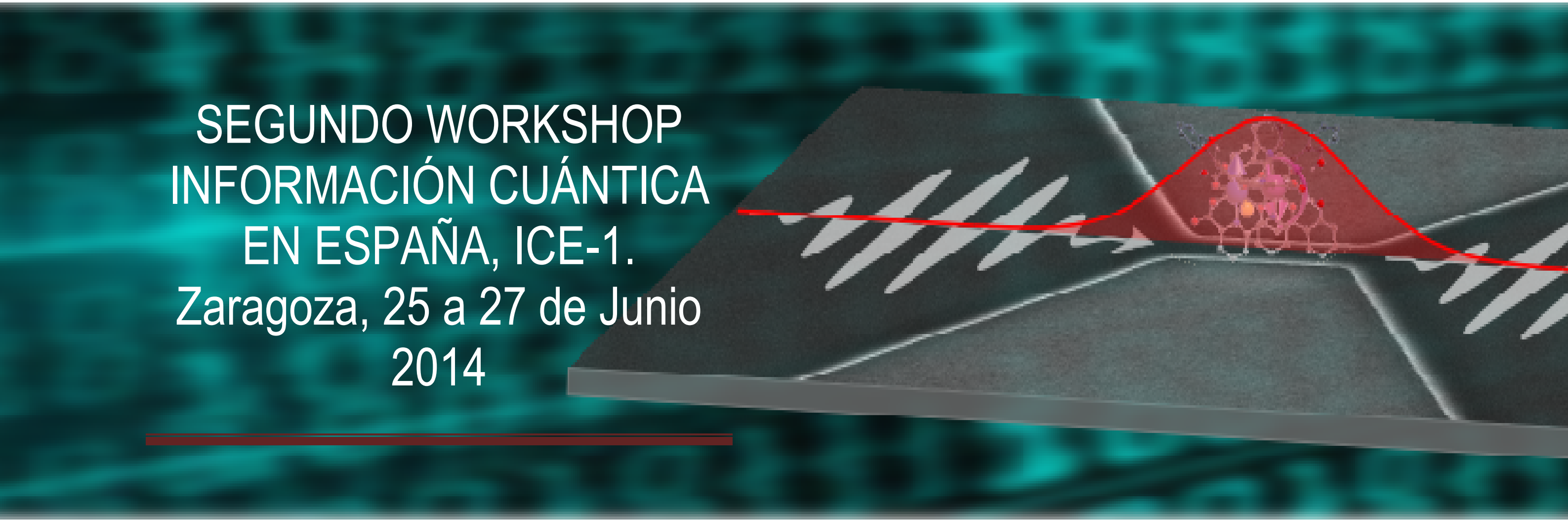
[b]IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain.

We introduce the concept of Quantum Biomimetics and, as an example, we propose a bio-inspired sequential quantum protocol for the cloning and preservation of the statistics associated to quantum observables of a given system. It combines the cloning of a set of commuting observables, permitted by the no-cloning and no-broadcasting theorems, with a controllable propagation of the initial state coherences to the subsequent generations. The protocol mimics the scenario in which an individual in an unknown quantum state copies and propagates its quantum information into an environment of blank qubits. Additionally, we propose a realistic experimenta implementation of this protocol in trapped ions. Finally, we will mention also other results including mutations and natural selection [2], quantum artificial life [3], and quantum neurons [4][5].

[1] U. Alvarez-Rodríguez, M. Sanz, L. Lamata, and E. Solano, 'Biomimetic Cloning of Quantum Observables', *Scientific Reports* **4**, 4910 (2014)
[2] U. Alvarez-Rodríguez, M. Sanz, Y. Omar, L. Lamata, and E. Solano, in preparation.
[3] P. Pfeiffer, M. Sanz, and E. Solano, "Growth and Evolution in a Quantum Model", in preparation
[4] U. Alvarez-Rodríguez, M. Sanz, L. Lamata, and E. Solano, "The Forbidden Quantum Sum", in preparation
[5] P. Pfeiffer, M. Sanz, and E. Solano, "The Quantum Hodgkin-Huxley Model", in preparation.



Emulation of gravitational waves in curved spacetimes with entangled photon states

Ivan Fernández-Corbatón,[1,2] Mauro Cirio,[1,2] Alexander Büse,[1,2] Lucas Lamata,[3] Enrique Solano,[3,4] and Gabriel Molina-Terriza[1,2]

[1]Department of Physics & Astronomy, Macquarie University, Australia
[2]ARC Center for Engineered Quantum Systems, Macquarie University, North Ryde, New South Wales 2109, Australia
[3]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain
[4]IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain

Gravitational waves, as predicted by Einstein's general relativity theory, appear as ripples in the fabric of spacetime traveling at the speed of light. We have formally proved that the propagation of small amplitude gravitational waves in a curved spacetime is equivalent to the propagation of a subspace of electromagnetic tensor waves. This subspace can be realized using entangled photon states. We use the result to propose a path to emulate the propagation of gravitational waves in curved spacetimes by means of experimental electromagnetic setups featuring metamaterials.

Experiments with the DWave prototype

(Invited)

Sergio Boixo

Google

Quantum annealing is an optimization method designed to take advantage of quantum phenomena, such as quantum superposition, tunneling and quantum fluctuations. Diabatic transactions between energy levels, and thermal excitations and relaxation, can play an important role in quantum annealing (as opposed to adiabatic quantum computation). DWave has implemented a physical quantum annealing prototype with up to 512 qubits. The decoherence time scale in this device is much shorter than the annealing time. I will review recent work done in this prototype. On the one hand, we find evidence of entanglement within eight superconducting flux qubits. On the other hand, we find no evidence of a quantum speedup for the case of random Ising glasses when the entire data set is considered, and obtain inconclusive results when comparing subsets of problems on an instance-by-instance basis. I will present preliminary new results and theory comparing noisy quantum annealing, the DWave prototype, and several numerical models.

On the number of uses of the channel needed to find positive coherent information

Toby Cubitt[a], David Elkouss[b], Will Matthews[c], Maris Ozols[a], David Pérez-García[b], Sergii Strelchuk[a]

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[b]*Departamento de Análisis Matemático and Instituto de Matemática Interdisciplinar, Universidad Complutense de Madrid, 28040 Madrid, Spain*
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The quantum capacity of a channel is given by the regularization of the coherent information of an unbounded number of uses of the channel. This regularization is necessary due to the nonadditive behaviour of the coherent information [1,2,3]. However, all results until now had shown superadditivity violations only up to a small finite number of uses [1,4]. In this talk, for any number of uses, we present a channel with zero coherent information but positive quantum capacity.

[1] D. P. DiVincenzo, P. W. Shor, and J. A. Smolin, Phys. Rev. A 57, 830 (1998).
[2] G. Smith, J. M. Renes, and J. A. Smolin, Phys. Rev. Lett. 100, 170502 (2008).
[3] M. B. Hastings, Nature Physics 5, 255 (2009).
[4] G. Smith and J. A. Smolin, Phys. Rev. Lett. 98, 030501 (2007).

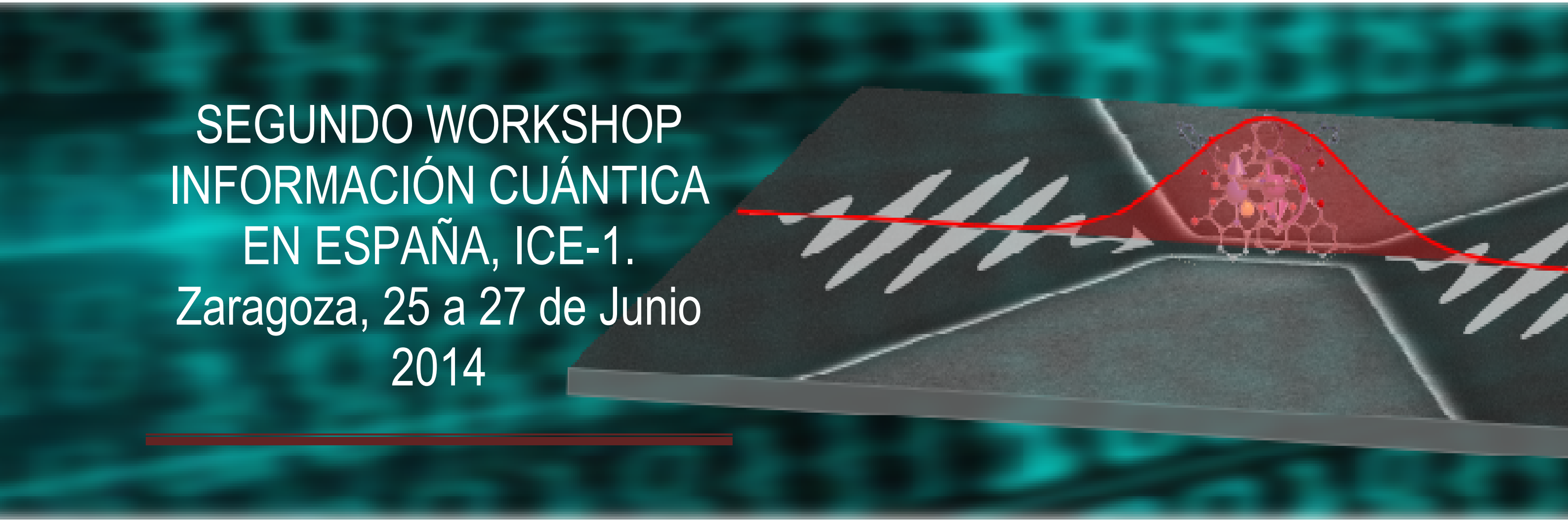
Implications of computer science principles for quantum physics

(Invited)

Ariel Bendersky

Instituto de Ciencias Fotónicas

One of the main pillars of computer science is the Church-Turing thesis, which postulates that every classical system is equivalent, in terms of computability power, to the so-called Turing machine. The implications of this hypothesis in other scientific fields, however, have hardly been explored. This is nonetheless a very natural scenario since experimental setups are always controlled by computers or other equivalent classical systems. In this talk I will show that, in the context of quantum physics, computer science laws have surprising implications for some of the most fundamental results of the theory. In particular, I will show situations in which ensembles of quantum states defining the same mixed state, indistinguishable according to the quantum postulates, do become distinguishable when prepared by a computer or, more generally, any device equivalent to a Turing machine.



POSTERS

Quantum Error Correction in a magnetic molecule

José J. Baldoví, Salvador Cardona-Serra, Juan M. Clemente-Juan, Eugenio Coronado, Luis Escalera-Moreno, Alejandro Gaita-Ariño, Guillermo Mínguez-Espallargas

ICMol, University of Valencia, c/ cat. José Beltrán nº2 - 46980 Paterna, Spain

Chemistry can be used to provide us some tunability in order to design specific Hamiltonians of physical interest by adjusting certain parameters of the chemical system under study within a realistic range. In this work, we study the ground energy level structure of a specific magnetic molecular system (three exchange-coupled $^{159}Tb^{3+}$ ions since in rare earths complexes is common to find a well-isolated electron spin doublet) and show that it is equivalent to nine electron-nuclear qubits in order to implement Shor's nine-qubit code [1]. Several proposals for Quantum Error Correction [2,3] have been made, but not yet by using magnetic molecules so extensively and, in this case, only by considering nuclear spins. The coupling between electron-nuclear spins does not allow us, in principle, to establish a trivial spin-qubit correspondence and, consequently, hinders the task of assigning zero-one tags to quantum states. But, by calculating quantum fidelity between the system with hyperfine coupling and with a negligible hyperfine coupling, we found fidelities close to the unity which allows us to separate nuclear and electronic qubits and, therefore, mitigate such a problem. We calculated how such a quantum fidelity changes as magnetic exchange J and quantum tunneling splitting Δ change within realistic ranges (see figure).

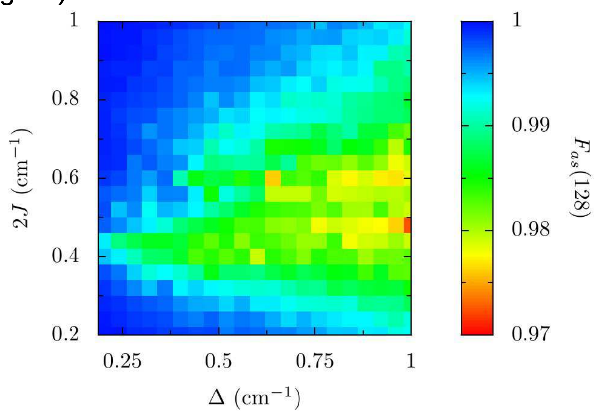


Figure: Variation of quantum fidelity with molecular parameters J and Δ, found to be maximal for Δ < 0.75 cm^{-1}

[1] José J. Baldoví, Salvador Cardona-Serra, Juan M. Clemente-Juan, Luis Escalera-Moreno, Alejandro Gaita-Ariño, Guillermo Mínguez Espallargas, arXiv:quant-ph/1404.6912

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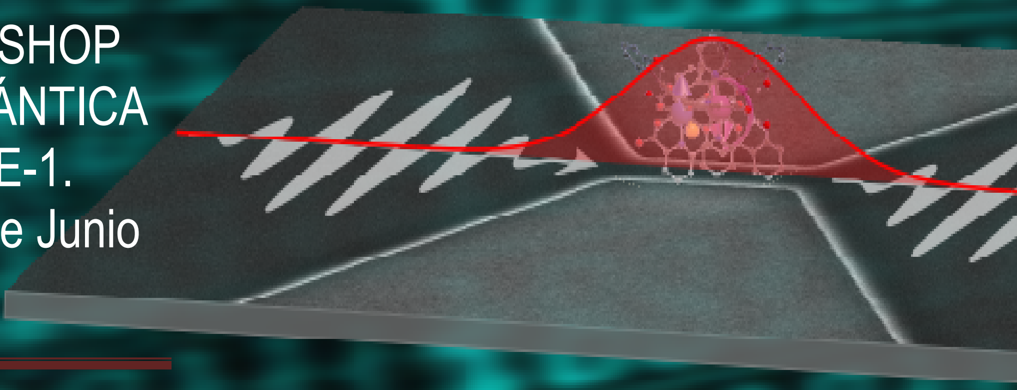

[2] G. Waldherr, Y. Wang, S. Zaiser, M. Jamali, T. Schulte-Herbrüggen, H. Abe, T. Ohshima, J. Isoya, J. F. Du, P. Neumann, J. Wrachtrup, Nature, **506**, 204 (2014)
[3] M. D. Reed, L. DiCarlo, S. E. Nigg, L. Sun, L. Frunzio, S. M. Girvin, R. J. Schoelkopf, Nature, **482**, 382 (2012)

Accuracy bounds for gradient magnetometry when single ensemble of atoms is used

Iagoba Apellaniz[a], Iñigo Urizar-Lanz[a], Zoltán Zimborás[a], Philipp Hyllus[a],and Géza Tóth[a,b,c].

[a]*Dept. of Theoretical Physics, University of the Basque Country, Leioa, Spain;*
[b]*IKERBASQUE, Basque Foundation for Science, Bilbao, Spain;*
[c]*Wigner Research Center for Physics, Hungarian Academy of Science, Budapest, Hungary.*

We study gradient magnetometry with atomic ensembles. The precision bounds for the estimation of the gradient for a single atomic ensemble is determined, assuming that the state is permutationally invariant. Our bounds are obtained from calculations based on the multi-parametric quantum Fisher information, and they are generally valid for all possible measurements. For quantum states that are invariant under the homogeneous fields, a single collective measurement is sufficient to estimate the gradient. For states that are sensitive to the homogeneous fields, two collective measurements are needed to obtain the gradients. This leads to a two parameter estimation problem. A single ensemble scenario has the advantage that a larger spatial resolution can be reached than in the two-ensemble case.

The Forbidden Quantum Sum

Unai Alvarez-Rodríguez[a], Mikel Sanz[a], Lucas Lamata[a], Enrique Solano[a,b]

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[b]*IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain*

We have studied the problem of performing the sum operation of the mathematical representation of quantum states with the tools given by Quantum Mechanics. Our results make evident that it is prohibited to sum unitarily unknown vector states while it is allowed to add density matrices. We analyze the applications and the computability of the quantum sum compared to the no-cloning theorem and the Deutsch-Church-Turing thesis.
[1] U. Alvarez-Rodríguez, M. Sanz, L. Lamata and E. Solano, The Forbidden Quantum Sum, *In preparation* (2014)

Digital Quantum Simulations with Superconducting Circuits

U. Las Heras[1], A. Mezzacapo[1], J. S. Pedernales[1], L. DiCarlo[2], S. Filipp[3], A. Wallraff[3], L. Lamata[1] and E. Solano[1]

[1]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain
[2]Kavli Institute of Nanoscience, Delft University of Technology, P. O. Box 5046, 2600 GA Delft, The Netherlands
[3] Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland
[4] IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain

We propose protocols for digital quantum simulations in a superconducting circuit architecture. We estimate the simulation feasibility of spin chain systems such as Heisenberg and Ising models, and of the quantum Rabi Hamiltonian, in a transmon qubit setup. We discuss experimental parameters and numerically prove the validity of a simulated dynamics within coherence times.

[1] U. Las Heras, A. Mezzacapo, L. Lamata, S. Filipp, A. Walraff, and E. Solano, Phys. Rev. Lett. *in press*, arXiv:1311.7626.
[2] A. Mezzacapo, U. Las Heras, J. S. Pedernales, L. DiCarlo, E. Solano, and L. Lamata, *in preparation.*

Two studies in Quantum Biomimetics: Neurons and the primordial soup

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Quantum Mechanics has grown to a point of maturity where it is not only used to explain and predict phenomena, but to engineer physical processes. Today's Quantum Information and Communication devices are the most prominent examples. We present two studies in progress using a new design tool for quantum mechanical devices, Quantum Biomimetics [1], based on the well-known idea of using biological systems as an inspiration for problem solving. The Hodgkin-Huxley model[2] of a neuron introduced a new circuit element, a resistor with memory, the Memristor. We are investigating possible quantum analogues[3] motivated by its promising applications in classical computer science. Life most probably originated from a hot mixture of chemical elements on the early Earth, the primordial soup. Favourable conditions lead to the appearance of more and more complex molecules, starting to show behaviours like self-maintenance which finally assembled to cells able of self-replication. We propose a simple toy model of a quantum primordial soup, a quantum gas of free spins interacting via a distance dependent Heisenberg Hamiltonian. Our aim is to study growth processes of bound states, the 'molecules', in this gas and ways of information transfer between them, preparing the way to a 'quantum cell'[4].

[1] U. Alvarez-Rodriguez, M. Sanz, L. Lamata, and E. Solano, 'Biomimetic Cloning of Quantum Observables', *Scientific Reports* **4**, 4910 (2014)
[2] Hodgkin & Huxley; *The Journal of physiology* **117**, 500-544 (1952)
[3] P. Pfeiffer, M. Sanz, and E. Solano, "The Quantum Hodgkin-Huxley Model", in preparation.
[4] P. Pfeiffer, M. Sanz, and E. Solano, "Growth and Evolution in a Quantum Model", in preparation.

Orbital entanglement and electron localization in quantum wires

Alberto Aleta, Héctor Villarrubia-Rojo, Víctor A. Gopar[a], Diego Frustaglia[b]

[a]*Departamento de Física Teórica, Universidad de Zaragoza*
[b]*Departamento de Física Aplicada, Universidad de Sevilla*

We study the signatures of disorder in the production of orbital electron entanglement in quantum wires. Disordered entanglers suffer the effects of localization of the electron wave function and random fluctuations in the entanglement production. This manifests in the statistics of the concurrence, a measure of the produced two-qubit entanglement. We calculate the concurrence distribution as a function of the disorder strength within a random-matrix approach. We also identify significant constraints on the entanglement production as a consequence of the breaking/preservation of time-reversal invariance. Additionally, our theoretical results are independently supported by simulations of disordered quantum wires based on a tight-binding model.

[1] Alberto Aleta, Héctor Villarrubia-Rojo, Diego Frustaglia, and Victor A. Gopar, Phys. Rev. B, **89**, 075429 (2014).

Scattering in the ultrastrong coupling

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The scattering of a flying photon by a two-level system ultrastrongly coupled to a one-dimensional photonic waveguide is studied numerically. The photonic medium is modeled as an array of coupled cavities and the whole system is analyzed beyond the rotating wave approximation using Matrix Product states. It is found that the scattering is strongly influenced by dressed bound states present in the system. In the ultrastrong coupling regime a new channel for inelastic scatting appears, where an incident photon deposits energy into the qubit, exciting a photon-bound state, and escaping with a lower frequency. This single-photon nonlinear frequency conversion process can reach up to 50% efficiency. Other remarkable features in the scattering induced by counter-rotating terms are a blue-shift of the reflection resonance and a Fano resonance due to long-lived excited states.

Quantum Error Correction in a magnetic molecule

José J. Baldoví[a], Salvador Cardona-Serra[a], Juan M. Clemente-Juan[a], Eugenio Coronado[a], Luis Escalera-Moreno[a], Alejandro Gaita-Ariño[a], Guillermo Mínguez-Espallargas[a]

[a]*ICMol, University of Valencia, c/ cat. José Beltrán nº 2 - 46980 Paterna, Spain,*

Chemistry can be used to provide us some tunability in order to design specific Hamiltonians of physical interest by adjusting certain parameters of the chemical system under study within a realistic range. In this work, we study the ground energy level structure of a specific magnetic molecular system (three exchange-coupled 159Tb3+ ions since in rare earths complexes is common to find a well-isolated electron spin doublet) and show that it is equivalent to nine electron-nuclear qubits in order to implement Shor's nine-qubit code [1]. Several proposals for Quantum Error Correction [2,3] have been made, but not yet by using magnetic molecules so extensively and, in this case, only by considering nuclear spins.
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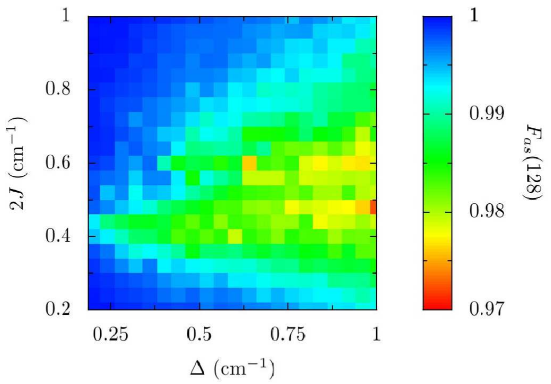

Figure: Variation of quantum fidelity with molecular parameters J and Δ, found to be maximal for $\Delta < 0.75$ cm^{-1}

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[2] G. Waldherr, Y. Wang, S. Zaiser, M. Jamali, T. Schulte-Herbrüggen, H. Abe, T. Ohshima, J. Isoya, J. F. Du, P. Neumann, J. Wrachtrup, Nature, 506, 204 (2014)
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Thermalization in closed quantum systems partially thermalized

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[b]Instituto de Ciencia de Materiales de Aragón, Universidad de Zaragoza, Plaza San Francisco s/n, 50009, Zaragoza, Spain
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We explore the dynamics of a one-dimensional quantum harmonic oscillator chain when part of it is thermalized. Using numerical simulation we perform a quench experiment testing if the non-thermalized part reaches to thermal equilibrium. We discuss the influence of different parameters of the system on the degree of thermalization. Also, we characterize the equilibrium state (long time dynamics).