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PHYSIQUE QUANTIQUE MESOSCOPIQUE

SESSION PLENIERE 2021

29 Novembre - 2 Décembre 2021

Aussois, France

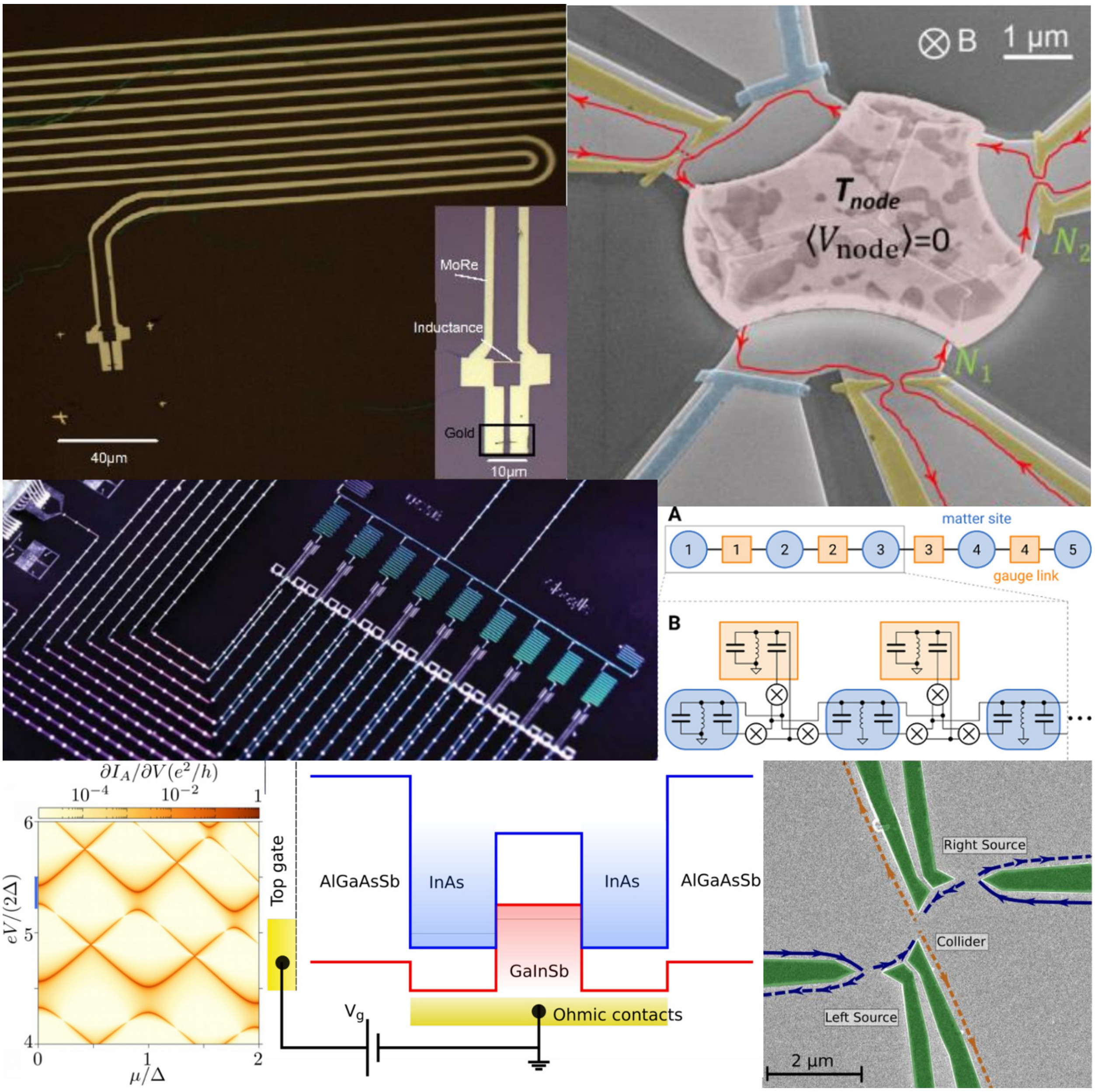

Table des matières

Programme

lundi 29 novembre 2021

HEURES	ÉVÉNEMENT
14:00 - 16:05	Matériaux et Systèmes Topologiques
14:00 - 15:00	› A guide to the periodic table of topological insulators - *Jérôme CAYSSOL, Laboratoire Ondes et Matière d'Aquitaine*
15:00 - 15:30	› Large energy gap in the topological phase of InAs/InxGa1−xSb/InAs triple quantum wells - *Colin Avogadri - Laboratoire Charles Coulomb*
15:30 - 16:00	› Nonlinear edge modes from topological 1D lattices - *Lucien Jezequel, Laboratoire de Physique de l'ENS Lyon (Phys-ENS)*
16:00 - 16:30	Pause café
16:30 - 18:35	Matériaux et Systèmes Topologiques
16:30 - 17:05	› Exotic physics induced by magnetic moments in a superconductor - *Pascal Simon - Laboratoire de Physique des Solides, University Paris Saclay*
17:05 - 17:35	› Tunnelling process visualized by shot-noise scanning tunnelling microscopy - *Freek Massee - Laboratoire de Physique des Solides*
17:35 - 18:05	› Quantized conductance with nonzero shot noise as a signature of Andreev edge state - *Manas Ranjan Sahu - Department of Physics, Indian Institute of Science, Bangalore*
18:05 - 18:35	› Spectral and transport signatures of 1d topological superconductors of finite size in the sub- and supra-gap regime - *Nico Leumer - Institut de Physique et Chimie des Matériaux de Strasbourg*
19:00 - 20:30	Dîner
20:30 - 22:30	Autre - Session poster

mardi 30 novembre 2021

HEURES	ÉVÉNEMENT
09:00 - 10:35	Matériaux et Systèmes 2D
09:00 - 10:00	› Twisted bilayer graphene and Moire materials - *Christophe Mora, Laboratoire Matériaux et Phénomènes Quantiques*
10:00 - 10:35	› Excitonic nature of magnons in a quantum Hall ferromagnet - *Alexandre Assouline, SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay.*
10:35 - 11:05	Pause café
11:05 - 12:05	Matériaux et Systèmes 2D
11:05 - 11:35	› Relaxation and revival of quasiparticles injected in an interacting quantum Hall liquid - *Dario Ferraro, CNR-SPIN, Universita degli studi di Genova*
11:35 - 12:05	› Shot noise investigation of anyonic statistics in the Fractional Quantum Hall regime - *Olivier Maillet, Centre for Nanoscience and Nanotechnology (CNRS-C2N), Palaiseau*
12:05 - 14:00	Déjeuner
14:00 - 15:05	Oscillateurs Quantiques
14:00 - 14:35	› A macroscopic object passively cooled to its quantum ground state of motion - *Eddy Collin, Institut Néel*
14:35 - 15:05	› Circuit QED implementation of the non-perturbative boundary sine-Gordon model - *Sébastien Léger, Institut NEEL, CNRS, University of Grenoble Alpes*
15:05 - 16:10	Transport et Thermodynamique Quantique
15:05 - 15:40	› Dynamical Coulomb Blockade in a temperature-biased quantum channel - *Anne Anthore, Université de Paris - C2N*
15:40 - 16:10	› Dynamical Coulomb blockade of current and noise in out-of-equilibrium quantum circuits - *Ines Safi, Laboratoire de Physique des Solides*
16:10 - 16:40	Pause café
16:40 - 18:40	Supraconductivité Mésoscopique
16:40 - 17:10	› Gate-Assisted Phase Fluctuations in All-Metallic Josephson Junctions - *Julien Basset, Laboratoire de Physique des Solides*
17:10 - 17:40	› A Josephson junction supercurrent diode - *Nicola Paradiso, University of Regensburg*
17:40 - 18:10	› High kinetic inductance resonators in the strong disorder limit - *Thibault Charpentier, Institut Néel*
18:10 - 18:40	› Direct measurement of phase-dependent fluctuation-dissipation theorem in a superconducting-normal metal junction. - *Xavier Ballu, Laboratoire de Physique des Solides*
18:40 - 18:50	Bilan Ecole de Cargèse - Sophie Guéron, Benjamin Huard, François Parmentier,
19:00 - 21:30	Dîner
20:30 - 22:30	Autre - Session poster
20:30 - 22:00	Conseil Scientifique GDR - .

mercredi 1 décembre 2021

HEURES	ÉVÉNEMENT
08:50 - 10:30	Interaction Lumière-Matière
08:50 - 09:25	› Diamond-based quantum sensing: Principles and application to high-pressure magnetic measurements - *Jean-François Roch, Laboratoire Lumière, Matière et Interfaces*
09:25 - 10:00	› Detecting spins by their fluorescence with a microwave photon counter - *Emmanuel Flurin, Service de physique de l'état condensé*
10:00 - 10:30	› Absence of Anderson localization in 1D dipole chains due to cavity photons - *Thomas Allard, Institut de Physique et Chimie des Matériaux de Strasbourg*
10:30 - 10:50	Pause café
10:50 - 12:25	Information et Circuits Quantiques
10:50 - 11:50	› Introduction to Quantum Computing: The Good, the Bad and the Ugly - *Xavier Waintal, Univ. Grenoble Alpes, CEA, INAC-PHELIQS, F-38000 Grenoble, FRANCE*
11:50 - 12:25	› Towards Quantum Computation with Fluxonium qubits - *Quentin Ficheux, ETH Zürich, Joint Quantum Institute*
12:25 - 16:00	Déjeuner et après-midi libre
16:00 - 18:00	Transport et Thermodynamique Quantique
16:00 - 17:00	› Quantum Information in Mesoscopic Quantum Thermal Machines - *Géraldine Haack, Université de Genève*
17:00 - 17:30	› Signature of resonant modes in radiative heat current noise spectrum - *Jonathan Wise, Université Grenoble Alpes and CNRS*
17:30 - 18:00	› Kwant: a numerical toolbox for quantum nanoelectronics - *Christoph Groth, Laboratoire Photonique Electronique et Ingénierie Quantique*
18:00 - 18:10	Discussion GdR
18:10 - 19:00	In Memoriam (Fabien Portier, Marc Sanquer)
19:00 - 20:30	Dîner festif

jeudi 2 décembre 2021

HEURES	ÉVÉNEMENT
08:50 - 10:25	Information et Circuits Quantiques
08:50 - 09:25	› Quantum simulation with solid-state quantum technologies : Observing many-body localization in a superconducting qubit array - *Michele Filippone - CEA Grenoble*
09:25 - 09:55	› Quantum reservoir neural network implementation on a Josephson Parametric Converter - *Danijela Markovic - Unité Mixte de Physique CNRS, Thales, Université Paris-Saclay*
09:55 - 10:25	› Determination of the disorder potential from quantum transport data using machine learning methods - *Gaetan Percebois - Institut de Physique et Chimie des Matériaux de Strasbourg*
10:25 - 10:45	Pause café
10:45 - 11:45	Information et Circuits Quantiques
10:45 - 11:15	› Engineering a U(1) lattice gauge theory in classical electric circuits - *Hannes Riechert - Laboratoire de physique de la matière condensée, Kirchhoff-Institute for Physics, Heidelberg University*
11:15 - 11:45	› Coulomb interactions and effective quantum inertia of charge carriers in a macroscopic conductor - *christophe chaubet - universite montpellier*

Abstracts

(in chronological order)

A guide to the periodic table of topological insulators

Jérôme Cayssol *† [1], Jean-Noel Fuchs‡ [2]

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This tutorial talk provides a brief introduction and overview to topological band theory and Dirac materials. Topology is the mathematical theory of geometric properties that are insensitive to smooth deformations. We first explain how this idea can be applied to the band structures of insulators in order to provide the famous "periodic table of topological insulators". Using the simplest example of two-band insulators, we will focus on some selected cases of this periodic table and emphasize the role of spatial dimension (D) of the lattice and symmetries. In 2D and in the absence of time-reversal symmetry, there are different classes of insulators as exemplified by the integer quantum Hall effect and the Haldane model for graphene. The presence of time-reversal symmetry can provide other types of topological insulators, like the quantum spin Hall insulators discovered by Kane and Mele for D=2, and generalized to D=3 by Fu and Kane. Then, we will discuss the 1D Shockley model, a chain of coupled s and p orbitals, to show how inversion symmetry can also protect a topologically non trivial phase beyond the ten-fold classification. We conclude by a brief review of topological superconductors that also show up in the "periodic table of topological insulators". All those topological insulators or superconductors are characterized by a quantized and robust macroscopic response in the bulk, and the presence of protected edge or surface states, which provides interesting low-dimensional systems for mesoscopic physics.

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Large energy gap in the topological phase of InAs/InxGa1–xSb/InAs triple quantum wells

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Two-dimensional topological insulators (2D TIs), also known as quantum spin Hall insulators, are characterized by an insulating bulk and spin-polarized helical states at the sample edges. While the first experimental observation of a 2D TI was made on HgTe/CdTe quantum wells, the InAs/GaSb double quantum well (DQW) structure was also predicted to host a 2D TI and the topological nature of these DQWs was demonstrated experimentally in 2011. These structures have attracted considerable interest because they benefit from easy fabrication processes, have high mobility, and their band structure can be tuned by an electric field. However, they also exhibit a low band gap, of at most $\sim$ 3meV. Our goal is to experimentally demonstrate the existence of a "wide" band gap 2D topological insulator based on III-V semiconductor quantum wells (QWs), as predicted in our group in InAs/GaSb trilayer QWs (TQWs). By magneto-transport measurements in a temperature range from 300 mK to 150K, we reveal an inverted band structure with a gap of 45 meV in these trilayers. By exploiting the different probe configurations of Hall bar devices, we argue that when the Fermi energy is in the gap, bulk conduction disappears and transport is dominated by edge conduction, which we attribute to topological edge states with an equilibrium length of a few micrometers.

Mots-Clés: Topological Insulators, InAs/GaSb, Magneto, transport, Edge transport

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Nonlinear edge modes from topological 1D lattices

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We propose a method to address the existence of topological edge modes in one-dimensional (1D) nonlinear lattices, by deforming the edge modes of linearized models into solutions of the fully nonlinear system. For large enough nonlinearites, the energy of the modified edge modes may eventually shift out of the gap, leading to their delocalisation in the bulk. We identify a class of nonlinearities satisfying a generalised chiral symmetry where this mechanism is forbidden, and the nonlinear edge states are protected by a topological order parameter. Different behaviours of the edge modes are then found and explained by the interplay between the nature of the nonlinarities and the topology of the linearized models.

Mots-Clés: Edge mode, Nonlinearity, Topology, Chiral symmetry

*Intervenant

Exotic physics induced by magnetic moments in a superconductor

Pascal Simon * [1]

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The study of magnetic impurities have received a recent resurgence of interest, fueled in part by possible sightings of topological superconductivity in chains of magnetic adatoms on superconducting substrates. After a short review of recent results for a single classical magnetic impurity embedded in a superconductor, I will then argue that such a system can be viewed as the simplest heterostructure made of a conventional s-wave superconductor and a ferromagnet which breaks time-reversal symmetry. As such, odd-frequency pairing correlations, as first envisioned by Berezinskii more than forty years ago, are generated around the impurity. An exact proportionality relation between the even-frequency component of the local electron density of states and the imaginary part of the odd-frequency local pairing function can be derived. Applying this relation to scanning tunneling microscopy spectra taken on top of magnetic impurities immersed in a Pb/Si (111) monolayer, I will show experimental evidences of the occurrence of the odd-frequency pairing in these systems and explicitly extract its superconducting function from the data [1].

In the second part of my talk, I will focus on shot-noise tomography, a recently developed STM technique, as a new tool to probe the effective charge of carriers as well as the nature of the tunnelling processes. I show that the spatial dependence of the Fano factor around various bound states induced by impurities can be used as a mean to characterized them. I will show that the Fano factor strongly oscillates spatially for both Andreev and Shiba bound states around the impurity location, with amplitudes greatly the Poissonian limit. This must be sharply contrasted with the behaviour of the Fano factor associated to Majorana bound states, which barely deviates from one. These sharp differences have a universal character which is rooted in the intrinsic particle-hole symmetry of the MBS wavefunction [2]. Pushing further the theoretical analysis of the Fano factor around a magnetic impurity in a superconductor, I will then show that we can have access to the intrinsic lifetime of a Shiba bound state [3].

[1] V. Perrin , F. L. N. Santos, G. Ménard, C. Brun, T. Cren, M. Civelli, P. Simon, Phys. Rev. Lett.**125**, 117003 (2020).

[2] V. Perrin, M. Civelli, P. Simon, Physical Review B **104**, L121406 (2021).

[3] U. Thupakula, V. Perrin, A. Palacio-Morales, L. Cario, M. Aprili, P. Simon, F. Massee, arXiv:2111.04749

Mots-Clés: Shiba bound states

*Intervenant

Tunnelling process visualized by shot-noise scanning tunnelling microscopy

Umamahesh Thupakula [1], Vivien Perrin [1], Alexandra Palacio-Morales [1], Laurent Cario [2], Marco Aprili [1], Pascal Simon [1], Freek Massee * [1]

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Isolated electronic states generated by single atom impurities, such as acceptor and donor states in semiconductors and in-gap states in superconductors, are ideal building blocks for bottom-up constructed devices. Particularly chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as they may host Majorana fermions. One of the challenges in this endeavour is to understand the intrinsic lifetime of the localised states, which is expected to be limited by the inelastic coupling with the continuum. Here I will present how using shot-noise scanning tunnelling microscopy combined with theoretical modelling we reveal the coexistence of both coherent and incoherent tunnelling processes into in-gap states, as well as extract their intrinsic lifetime.

Mots-Clés: Scanning tunnelling microscopy, shot noise, superconductivity

*Intervenant

Quantized conductance with nonzero shot noise as a signature of Andreev edge state

Manas Ranjan Sahu * [1], Arup Kumar Paul [1], Jagannath Sutradhar [1], K Watanabe [2], T Taniguchi [2], Vibhor Singh [1], Subroto Mukerjee [1], Sumilan Banerjee [1], Anindya Das [1]

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Electrical conductance measurements have limited scope in identifying Andreev edge states (AESs), which form the basis for realizing various topological excitations in quantum Hall (QH) – superconductor (SC) junctions. To unambiguously detect AESs, we measure shot noise along with electrical conductance in a graphene based QH-SC junction at integer filling $\nu = 2$. Remarkably, we find that the Fano factor of shot noise approaches half when the bias energy is less than the superconducting gap, whereas it is close to zero above the superconducting gap. This is striking, given that, at the same time, the electrical conductance remains quantized at $2\frac{e^2}{h}$ within and above the superconducting gap. A quantized conductance is expected to produce zero shot noise due to its dissipationless flow. However, at a QH-SC interface, AESs carry the current in the zero-bias limit and an equal mixing of electron and hole like states produce half of the Poissonian shot noise with quantized conductance. The observed results are in accord with our detailed theoretical calculations of electrical conductance and shot noise based on the non-equilibrium Green's function method in the presence of disorder.

Mots-Clés: Andreev reflection, Quantum Hall effect, Graphene, Andreev edge state, Shot noise

*Intervenant

Spectral and transport signatures of 1d topological superconductors of finite size in the sub- and supra-gap regime

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The Kitaev chain is the archetypal model of 1d topological superconductors and often used to explain the phyics behind the exotic edgestates known as Majorana fermions [1]. As indicated by the word "edge", the spatial profile of Majorana fermions decays away from the system's ends. However, the research on topological superconductors is typically limited to semi-infinite treatments from the analyitcal side or pure numerical approaches. Thus, the interplay or better competition between open boundary condition on the one side and the topological predictions on the other side, is not properly respected nor fully understood. One aspect of my talk is dedicated to this issue and I give the answer to this "conflict". In case of the Kitaev chain, I invented a special technical approach using so called "Tetranacci" polynomials, which allowed me to derive exact analytical formulae for the spectrum, the associated eigenvectors and also the retarded Green's functions and conductance in a N-S-N (normal-superconducting-normal) setup below and above the superconducting gap [2,3]. In the first part of my talk, I summarize the main results without touching technical details. As perspective, the open boundary conditions impose a non-trivial quantization condition on the wave vectors, which differes by far from the usual "particle in the box" behaviour. The important consequence is a smooth and not a sharp topological phase transition.

In the second part of my talk, we leave the Kitaev chain and turn to the semiconducting Rashba-nanowires which can be seen as a realization of the Kitaev chain [4-7]. I shortly summarize my results for the spectrum and the transport signatures. For instance, the nanowire and the Kitaev chain obey a common quantization rule, which is more general and shared with further models.

[1] A. Y. Kitaev, Phys. Usp. **44**, 131 (2001)

[2] N. Leumer, M. Marganska, B. Muralidharan, and M. Grifoni, J. Phys.: Condens. Matter **32**, 445502 (2020)

[3] N. Leumer, M. Grifoni, B. Muralidharan, and M. Marganska, Phys. Rev. B **103**, 165432

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(2021)

[4] R. Aguado, La Rivista del Nuovo Cimento **40**, 523 (2017)

[5] Y. Oreg, G. Refael and F. von Oppen, Phys. Rev. Lett. **105**, 177002 (2010)

[6] R. M. Lutchyn, J. D. Sau, and S. Das Sarma, Phys. Rev. Lett. **105**, 077001 (2010)

[7] J. Alicea, Rep. Prog. Phys. **75**, 076501 (2012)

Mots-Clés: Majorana fermions, Topological edgestates, Linear transport, Non, linear transport, Kitaev chain, Rashba, nanowire

Twisted bilayer graphene and Moiré materials

Christophe Mora *† [1]

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Twisted bilayer graphene is obtained in a relatively simple setting: two monolayers of graphene are superimposed with a slight relative orientational mismatch, forming a Moiré pattern. The same idea can be applied to stacking configurations with more layers of graphene, or to other two-dimensional materials including transition metal dichalcogenides, defining the emergent field of twistronics. The experimental achievements in this burgeoning field have been very fast in the last three/years and exotic correlated phases have been observed such as superconductivity with unconventional properties, correlated insulators, topological phases with an associated anomalous quantum Hall effect, nematic structures, orbital and spin ferromagnetism or excitonic insulators. Much of this originates from the tuning to almost flat bands at certain magic twist angles.

In this talk, I will introduce the physics of twisted bilayer graphene, review the remarkable experimental successes of the past few years and discuss its theoretical modeling with flat bands and symmetry breaking states.

[1] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Nature **556**, 43 (2018)

[2] Y. Cao, V. Fatemi, A. Demir, S. Fang, S.L. Tomarken, J.Y. Luo, J.D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R.C. Ashoori and P. Jarillo-Herrero., Nature **556**, 80 (2018)

[3] J.M. Park, Y. Cao, K. Watanabe, T. Taniguchi, and P. Jarillo-Herrero, Nature **590**, 249 (2021)

[4] E. Y. Andrei and A. H. MacDonald, Nature Materials **19**, 1265 (2020)

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Excitonic nature of magnons in a quantum Hall ferromagnet

Alexandre Assouline *† [1], Myunglae Jo , Paul Brasseur , Kenji Watanabe , Takashi Taniguchi , Thierry Jolicoeur , Christian Glattli , Norio Kumada , Patrice Roche , François Parmentier , Preden Roulleau

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Magnons enable the transfer of a magnetic moment or spin over macroscopic distances. In quantum Hall ferromagnets, it has been predicted that spin and charge are entangled, meaning that any change of the spin texture modifies the charge distribution. As a direct consequence of this entanglement, magnons should carry an electric dipole moment. Here we report evidence of this electric dipole moment in a graphene quantum Hall ferromagnet using a Mach-Zehnder interferometer. As magnons propagate across the insulating bulk, their electric dipole moment modifies the Aharonov-Bohm flux through the interferometer, affecting both the phase and visibility of the interference pattern. In particular, we relate the phase shift to the sign of this electric dipole moment, the loss of visibility to the flux of emitted magnons, and we show that the magnon emission is a Poissonian process. The ability to couple the spin degree of freedom to an electrostatic potential is a property of quantum Hall ferromagnets that could be promising for spintronics.

Mots-Clés: quantum, Hall, ferromagnet, magnon, spin, interferometer

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Relaxation and revival of quasiparticles injected in an interacting quantum Hall liquid

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The one-dimensional, chiral edge channels of the quantum Hall effect are a promising platform in which to implement electron quantum optics experiments; however, Coulomb interactions between edge channels are a major source of decoherence and energy relaxation. It is therefore of large interest to understand the range and limitations of the simple quantum electron optics picture. We confirm experimentally for the first time the predicted relaxation and revival of electrons injected at finite energy into an edge channel [1]. The observed decay of the injected electrons is reproduced theoretically within a Tomonaga-Luttinger liquid picture, including a linear energy loss rate towards external degrees of freedom [2].

[1] R. H. Rodriguez, F. D. Parmentier, D. Ferraro, P. Roulleau, U. Gennser, A. Cavanna, M. Sassetti, F. Portier, D. Mailly, P. Roche, Nature Comm. **11**, 2426 (2020).

[2] G. Rebora, D. Ferraro, R. H. Rodriguez, F. D. Parmentier, P. Roche, M. Sassetti, Entropy **23**, 138 (2021).

Mots-Clés: Electron Quantum Optics, Interaction effects in integer Hall states, Relaxation of electronic wave, packets

*Intervenant

Shot noise investigation of anyonic statistics in the Fractional Quantum Hall regime

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Anyons are exotic quasiparticles whose exchange statistics interpolate between that of fermions and bosons. In the 80s, they have been predicted to exist as low-energy excitations of the Fractional Quantum Hall (FQH) liquids [1] in two-dimensional electron gases at high magnetic fields. These quasiparticles possess a fractional charge [1], which was experimentally confirmed 25 years ago [2]. However, their anyonic nature, corresponding to an exchange phase between 0 and π, remained elusive until recently. In 2020, two experiments [3, 4] reported the observation of a fractional exchange statistics in the $\nu = 1/3$ FQH state, where a $\pi/3$ exchange phase is predicted. One of them [4], based on a recent proposal [5], features the so-called "mesoscopic collider", which shares similitudes with the Hong-Ou-Mandel interferometer. The central part of the device is a 'collider' QPC, behaving as an electronic beam splitter that mixes two incoming beams of FQH quasiparticles, each generated at its respective 'source' QPC. It is predicted that the exchange phase is imprinted in the low-frequency cross-correlations between the current fluctuations of the two outgoing beams [5]. Here, we reproduce quantitatively and extend the pioneer results at $\nu = 1/3$ [4]. Whereas the cross-correlations vanish for quasiparticles of charge e injected at the source QPCs, a signal of amplitude corresponding to the predictions for an exchange phase $\pi/3$ is observed at fractional injected charges e/3. Intriguingly, these cross-correlations are found to persist even if the collider QPC is set in the strong backscattering regime, where the partition charge from direct shot noise measurements is e, different from the quasiparticle's charge e/3 generated at source QPCs. These results may call for a new interpretation [6], where cross-correlations arise from anyonic braiding rather than collisions as initially thought.

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*Intervenant

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Mots-Clés: Quantum Point Contacts, anyonic statistics, shot noise, Fractional Quantum Hall Effect

A macroscopic object passively cooled to its quantum ground state of motion

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Recent advances in observing and exploiting macroscopic mechanical motion at the quantum limit brought opto-mechanical experiments down to always lower temperatures and smaller sizes, boosting a new research area were (more compatible) low energy photons are employed: microwave opto-mechanics. Superconducting microwave circuits are in use and bridge opto-mechanics with quantum electronics, which positions the former as a new resource for quantum information processing. But microwave opto-mechanical platforms provide also unique capabilities for testing quantum mechanics at the most basic level: if one thinks about these devices in terms of quantum-limited detectors, the focus is on the *thermodynamic baths* that continuously interact with the mechanical degree of freedom. The fundamental questions that are addressed are then quantum thermodynamics, the boundary between classical and quantum mechanics defined by wavefunction collapse, and ultra-low temperature materials properties.

In order to perform such experiments at the frontier of modern physics, we created a unique micro-wave/micro-Kelvin opto-mechanical platform. We demonstrate for the first time the passive cooling of a 15 MHz aluminium drumhead mechanical device down to 500 micro-K, reaching a population for the fundamental mode of 0.3 quanta on average [1]; all higher modes being empty to a very high probability. Using microwave opto-mechanics as a non-invasive detector, we report on the *in-equilibrium* thermal properties of this lowest frequency mode, in particular the *fluctuations of the population number.*

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Mots-Clés: nanomécanique, optomécanique, ultra basse température

*Intervenant

Circuit QED implementation of the non-perturbative boundary sine-Gordon model

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Quantum impurity problems, that describe the interaction between a degree of freedom (DOF) and an environment, are at the heart of a very rich physics covering fields as diverse as quantum optics and strongly correlated matter . In this work, we use the tools of circuit QED to address a quantum impurity problem called Boundary Sine Gordon (BSG).

To do so, we wire a highly non-linear SQUID, the DOE, to a multi-mode high impedance cavity, the environment (∼4000 modes). The use of a SQUID together with our engineered environment enable us to study the BSG problem from the perturbative regime to a regime where the physics involved remains poorly understood. Thanks to our setup, we could measure the renormalization of the SQUID frequency induced by the interplay between its nonlinearity and the strong interaction with its environment. In addition to this, we have also observed the dissipation induced by the SQUID in the environment modes. The dissipation is materialized by highly non-perturbative photon conversion phenomena where a photon inserted in the cavity can reach a 10% probability of decaying after one round trip. Detailed modelling explains both the dissipation and renormalization quantitatively and confirms that the physics involved is highly non-linear, many-body and quantum.

Mots-Clés: Boundary sine Gordon, Quantum impurity, Circuit QED

*Intervenant

Dynamical Coulomb Blockade in a temperature-biased quantum channel

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The transport properties of quantum conductors can strongly change when embedded in an on-chip dissipative mesoscopic circuit. At the heart of this phenomenon is the Coulomb energy required to change the charge in small interconnect nodes of the circuit. Handling the dynamics of charge theoretically is a huge challenge beyond perturbative regimes. Yet the suppression of the electrical conductance (also called dynamical Coulomb blockade) of a single quantum channel in series with a resistance has been successfully predicted thanks to a mapping with a solvable one-dimensional model of a Tomonaga Luttinger Liquid comprising a single scattering impurity [1,2]. This mapping holds as long as all parts of the circuit are at the same temperature. However, in voltage-bias nanocircuits, Joule power dissipation heats up small nodes, creating an electronic temperature imbalance. In this talk, I will present an experimental investigation of dynamical Coulomb blockade of a quantum channel in series with a resistance under a controlled temperature bias and compare the results to new theoretical developments [3,4].

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[3] H. Duprez et. al., Phys. Rev. Research **3**, 023122 (2021)

[4] see also I. Safi's contribution

Mots-Clés: Dynamical Coulomb Blockade, Quantum transport

*Intervenant

Dynamical Coulomb blockade of current and noise in out-of-equilibrium quantum circuits

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We address, for the first time, dynamical Coulomb blockade in a quantum circuit with an out-of-equilibrium distribution. The circuit is formed by a conductor strongly coupled to a linear electromagnetic environment with an arbitrary impedance. On the theoretical level, we develop a novel approach to express formally the Keldysh generating functional for current cumulants [1]. We also express current average and noise in the regime of a good transmitting conductor subject to a finite voltage, which obey universal fluctuation relations derived within the perturbative approach [2]. We then apply these two approaches to a circuit with inhomogeneous temperatures, studied experimentally at C2N when the conductor is formed by a QPC in the integer Hall regime. The theoretical predictions for the conductance are in a very good agreement with its measured values at zero voltage in [3, 4]. We also show that the temperature-activated shot noise, dubbed delta-T noise, is negative for an arbitrary environmental impedance.

Indeed, due to temperature inhomogeneities, or, more generally, to initial out-of-equilibrium distributions, the mapping of the circuit to a one-dimensional interacting conductor [5, 6] fails. In addiiton, we analyze further the circuit with an initial thermal equilibrium distribution, for which we show that, for a family of environmental impedances, an exact duality holds between the regime of a good transmitting conductor and the tunneling regime. This explains and extends the duality we have obtained in Ref.[3].

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*Intervenant

Mots-Clés: Dynamical Coulomb blockade, Quantum circuits, Out, of, equilibrium transport, Delta T Noise

Gate-Assisted Phase Fluctuations in All-Metallic Josephson Junctions

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The discovery that a gate electrode suppresses the supercurrent in purely metallic systems is missing a complete physical understanding of the mechanisms at play. We here study the origin of this reduction in a Superconductor-Normal metal-Superconductor Josephson junction by performing, on the same device, a detailed investigation of the gate-dependent switching probability together with the local tunnelling spectroscopy of the normal metal. We demonstrate that high energy electrons leaking from the gate trigger the reduction of the critical current which is accompanied by an important broadening of the switching histograms. The switching rates are well described by an activation formula including an additional term accounting for the injection of rare high energy electrons from the gate. The rate of electrons obtained from the fit remarkably coincides with the independently measured leakage current. Concomitantly, a negligible elevation of the local temperature is found by tunnelling spectroscopy which excludes overheating scenarios.

*Intervenant

A Josephson junction supercurrent diode

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A supercurrent diode is a device where the critical current depends on the bias polarity. In a recent seminal paper, Ando et al. [1] demonstrated the effect on superconducting superlattices with Rashba spin-orbit coupling. However, a detailed explanation of the physical mechanism behind the effect is still elusive. Here, we demonstrate the supercurrent diode effect in Josephson junctions [2]. These are obtained patterning InAs heterostructures hosting a shallow 2D electron gas proximitized by an epitaxial Al film.

We characterize the supercurent diode effect in terms of magnetochiral anisotropy of the Josephson inductance. This is measured using a cold RLC circuit resonating in the MHz regime. The bias dependence of the Josepshon inductance links the nonreciprocal supercurrent to the asymmetry of the current–phase relation, and directly provides the supercurrent magnetochiral anisotropy coefficient. Kwant simulations with realistic parameters well reproduce the main features of our experiments. Superconducting Josephson diodes can be key components of novel fully superconducting circuits with low energy loss, including logic elements, detectors and signal demodulators.

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Mots-Clés: Superconducting diode, Josephson junctions, InAs heterostructures, Rasbha systems

*Intervenant

High kinetic inductance resonators in the strong disorder limit

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Strongly disordered superconductors are a promising playground for the fabrication of high kinetic inductance circuits and qubits. Upon increase of disorder one is able to achieve considerably large inductances with a simple fabrication process. However, when disorder is further increased thin films undergo a transition to insulation, accompanied by puzzling other features still debated to this day. It is therefore mandatory to have a better understanding of superconductivity in highly disordered films in view of application prospects. In this talk I discuss how strong disorder deeply modifies the superconducting state. By measuring the kinetic inductance of superconducting resonators made of amorphous indium oxide at very low temperature, we show that the transition to superconductivity is bosonic with a critical temperature ruled by superconducting phase fluctuations

Mots-Clés: kinetic inductance, disorder, quantum phase transition, superconductivity

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Direct measurement of phase-dependent fluctuation-dissipation theorem in a superconducting-normal metal junction.

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A metal coupling two superconductors hosts Andreev bound states, carrying a phase-dependent periodic supercurrent. At finite frequency dynamical processes between Andreev levels give rise to delay, and consequently dissipation, in the junction. According to the fluctuation-dissipation theorem, a supercurrent noise is also expected at equilibrium. While dissipation has already been measured in previous works via the ac susceptibility [1], noise is yet to be observed.

In our experiment, we measure independently the phase-dependent dissipation (via the susceptibility χ'') and noise on the same gold-based SNS junction coupled to a resonator (see Figure (left)). This resonator is characterized by its resonance frequency ν_R (117.3 MHz) and quality factor Q (300). The susceptibility is deduced from the shifts in resonance frequency and Q-factor when the junction is biased by the ac flux of the resonator. The noise measurement consists on measuring directly the voltage fluctuations S_v at equilibrium across the resonator, without any bias (see Figure (middle)). These measurements are realized with an ultrasensitive cryogenic amplifier made by Yong Jin (C2N) ($S_{I,\text{amp}} = 4.75 \times 10^{-28}\text{A}^2/\text{Hz}$ at 117.3 MHz). It is thus possible to compare directly the measured chi" and current noise S_I on the same sample. Our result (Figure (right)) quantitatively confirms the phase-dependent fluctuation-dissipation theorem in the SNS junction. We have identified the dissipation as a combination of a temperature-dependent effective resistance in parallel with the sample's phase-dependent kinetic inductance. This also provides a reliable measurement of the temperatures of the Andreev bound states.

It is predicted that noise and susceptibility contain signatures of topological properties such as protected level crossing at phase π [2]. Our equilibrium measurement should be very sensitive to any gap opening, which often remains elusive experimentally.

[1] Dou et al., in preparation.

[2] Murani et al, Phys. Rev. Lett. **122**, 076802 (2019)

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Mots-Clés: Quantum transport, current noise, SNS junction

Diamond-based quantum sensing: Principles and application to high-pressure magnetic measurements

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The nitrogen-vacancy (NV) color center is a point defect of diamond that behaves as an artificial atom with a discrete spectrum of quantum states. Due to this remarkable property, the NV center can be used as a magnetic field, pressure, stress, and temperature solid-state quantum sensor down to the atomic scale. I will briefly describe the principle of this atomic-like sensor which has a unique combination of sensitivity and spatial resolution.

The properties of diamond also lead to measurements where mostly no other sensor technology exists. For instance NV-based quantum sensing can be implemented inside a diamond anvil cell in order to investigate the magnetic and superconducting properties of high-pressure materials. Indeed, the diamond anvil cell is a table-top system that implements in laboratory conditions pressures above the megabar range, leading to the onset of specific quantum states of matter. However, confining the sample in the tiny dimension of the diamond anvil cell makes the implementation of any non-optical sensing technique highly challenging.

The properties of NV centers allowed us to directly observe the Meissner effect associated to the onset of high-pressure superconductivity inside a diamond anvil cell, at pressures up to about 50 GPa. This sensing method is compatible with synchrotron-based characterization of the crystalline structure and is therefore well suited to explore the superconducting properties of super-hydrides.

Mots-Clés: diamond, quantum sensing, high pressure, superconductivity

*Intervenant

Detecting spins by their fluorescence with a microwave photon counter

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Single-photon counters are essential for detecting weak incoherent electromagnetic radiation. In the optical domain, they are widely used to detect spontaneous emission from individual quantum systems, with applications in fluorescence microscopy, and in numerous areas of quantum technologies. In the microwave domain, operational single-photon counters have just recently been developed using superconducting quantum circuits [1], offering novel opportunities for detecting fluorescence or spontaneous emission at microwave frequencies. Here, we demonstrate the use of a microwave single-photon counter to detect the photons spontaneously emitted by a small ensemble of electron spins coupled to a superconducting micro-resonator [2]. In this novel spin detection scheme, each click of the detector reveals the quantum jump of an individual spin from its excited to its ground state. Besides their fundamental interest, our results also constitute a novel methodology for Electron Spin Resonance spectroscopy well suited for the detection of small numbers of spins.

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*Intervenant

Absence of Anderson localization in 1D dipole chains due to cavity photons

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In one-dimensional systems with short range interaction, it is known from the theory of Anderson localization that a small amount of disorder makes all the eigenstates of the system exponentially localized. However, for more complex interactions the effects of disorder become highly nontrivial. Recently, proposals have been made about using the light-matter interaction to modify the localization properties of a disordered system, notably leading to an improvement of the transport characteristics [1,2].

Here, we study the interplay between disorder and light-matter coupling by considering a disordered one-dimensional chain of dipoles placed inside a mirror cavity. Such a system hosting polaritonic (hybrid light-matter) excitations can be typically realized experimentally using plasmonic or dielectric nanoparticles, microwave helical resonators, and any other system for which the dominant mechanism is of dipolar nature. Through a numerical analysis of the eigenstates of the system, we find that in the strong coupling regime, some particular eigenmodes are immune to Anderson localization, despite their predominantly dipolar nature.

These mainly dipolar delocalized states highlight the complex link between disorder and polaritonic systems, and could lead to enhancement of transport in arrays of dipoles in the presence of fabrication inaccuracies.

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Mots-Clés: Anderson localization, Disordered systems, Strong coupling, Polaritons

*Intervenant

Introduction to Quantum Computing: The Good, the Bad and the Ugly

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In this tutorial, I will introduce quantum computing from two different perspectives: the one of the mathematicians that design algorithms and quantum circuits and the one of physicists that are trying to actually build these machines. I will show that while very nice progress is being made experimentally in all kind of platforms, the gap between what we can do and what would be needed for applications remains, well, quite significant and is likely to stay so for a while. I will discuss and contrast the two different routes that are envisioned for applications: the fault tolerant quantum computer and the noisy quantum computer.

*Intervenant

Towards Quantum Computation with Fluxonium qubits

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Mesoscopic electrical circuit have emerged as one of the leading technology to create a quantum computer [1]. Their progress is even more spectacular as it is solely based on a single qubit type, the transmon, whose weak anharmonicity has become a major limiting factor for the performance of current superconducting quantum processors. A promising path to reduce gate errors in transmon-based processors consists in developing highly anharmonic mesoscopic circuits with some degree of protection from prevailing decoherence sources. At present, properly designed single fluxonium qubits can have over 1 ms coherence time via the trick of slowing down the qubit transition about tenfold or more compared to typical superconducting circuits [2]. We describe recent progress in coherence time of fluxonium circuits as well as the implementation of high-fidelity single and two-qubit gates. This includes a fast microwave-activated controlled-Z gate completed in less than 9 qubit Larmor cycles (about 60 ns) with a fidelity of 99.2% [3,4], which is on-par with the best microwave-activated gates reported on other superconducting qubits. Finally, we discuss the prospects of extending our Fluxonium architecture to large scale quantum processors.

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Mots-Clés: superconducting circuits, quantum computation, quantum processor, high, fidelity quantum gates, fluxonium

*Intervenant

Quantum Information in Mesoscopic Quantum Thermal Machines

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While information is routinely exploited within control engineering to optimize processes via feedback, fundamental questions regarding the role of information for operating efficient nanoscale quantum devices are still open. Indeed, in quantum systems, observations generally alter the system state, and hence acquiring and exploiting information is a much more subtle issue. In particular, mesoscopic thermal machines that exhibit quantum coherence do not necessarily benefit from increasing the available classical information because observations collapse the sensitive quantum states. Alternatively, quantum information is a very valuable and hard-to-produce resource for information processing and sensing. It generally requires time-controlled schemes, avoiding dissipation and thermal environments. It is still an open question to determine the trade-off between the cost of producing quantum information resources and the advantage it could provide for realizing efficient quantum thermal machines. I will take the opportunity of this tutorial to first provide a short introduction into these questions, and second to present a family of genuine quantum thermal machines, i.e. devices that output quantum correlations from out-of-equilibrium thermal baths, now known as entanglement engines. These devices are designed to demonstrate conversion of heat into entangled quantum states open the question to which extend thermally-generated quantum information resources can be used as fuel for information processing and sensing protocols.

*Intervenant

Signature of resonant modes in radiative heat current noise spectrum

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Radiative heat current may be significantly enhanced in the near field due to evanescent wave coupling, i.e. photon tunnelling between bodies. In many situations the heat transfer is dominated by a narrow resonance in the transmission, e.g. a superconducting resonator mode [1] or a surface mode [2]. However, this resonant character of the heat transfer is not straightforward to deduce from a measurement of the average heat current. Here, we show that resonant modes produce a sharp feature in the radiative heat current noise spectrum, whose width is related to the lifetime of the resonant mode.
We illustrate this general conclusion with two examples. The first is a superconducting resonator modelled by an effective quantum circuit where the heat transfer occurs via the resonator mode [1]. The second is a pair of two-dimensional metallic layers modelled by Drude conductivity where the transfer is due to strongly coupled surface plasmon modes [3].

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*Intervenant

Kwant: a numerical toolbox for quantum nanoelectronics

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Kwant is an open-source Python package aiming to be an user-friendly, universal, and high-performance toolbox for the simulation of arbitrary physical systems that can be described by a tight-binding model. Since its release in the year 2013 the software has been used worldwide in research that has led to hundreds of peer-reviewed publications.

The Kwant toolbox has been in continuous development since its inception. On one hand, it has become easier and more expressive to use for problems to which already the original version could be applied. On the other hand it is now possible to tackle a wider range of problems. Examples of improvements include: addition of the concept of models, comprising their creation (automatic discretization of continuum Hamiltonans), use, and analysis of their symmetries; operators and facilities to visualize their expectation values; new solvers like the kernel polynomial method. A special mention is reserved for tkwant, a separate but related package that extends Kwant to time-dependent quantum transport.

I will briefly introduce Kwant, present the most important improvements of recent years, and give a glimpse into ongoing and possible future developments.

Mots-Clés: computational quantum nanoelectronics

*Intervenant

Quantum simulation with solid-state quantum technologies : Observing many-body localization in a superconducting qubit array

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I will discuss how quantum technologies based on solid state arrays of superconducting qubits (see figure below) are now able to unveil and investigate novel fundamental phenomena by simulating interacting quantum systems. In particular, we will ask : Is it possible to harness and preserve the quantum coherent properties of many-body systems ? This project seems doomed to fail, as interactions in many-body systems generally lead to ergodicity, namely the inevitable loss of quantum coherence and memory about initial conditions. Nevertheless, the recent discovery of many-body localization (MBL) – a generalization of Anderson localization in the presence of interactions – has shown the possibility to circumvent ergodicity. I will illustrate an experiment in which an array of superconducting qubits probes the exotic dynamics of interacting and disordered bosons [1]. Relying on real-time and interferometric probes, I will discuss how we could observe and characterize the mechanism of MBL. If time permits, I will then describe the possibility to trigger ergodicity in quantum simulators, by injecting single interacting impurities in localized and isolated quantum systems [2].

[1] B. Chiaro, C. Neill, A. Bohrdt, M. Filippone et al., arXiv:1910.06024

[2] U. Krause, T. Pellegrin, P. W. Brouwer, D. A. Abanin and M. Fiiippone, Physical Review Letters **126**, 030603 (2021)

Mots-Clés: quantum simulation, out of equilibrium quantum correlated systems, many body localization, superconducting qubit systems

*Intervenant

Quantum reservoir neural network implementation on a Josephson Parametric Converter

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Neuromorphic computing implements neural networks in hardware to make their training more time and energy efficient. However, addressing state-of-the-art machine learning tasks requires coupling large numbers of neurons, which is challenging with physical nano-devices. It has been proposed to solve this problem using quantum hardware and encoding neurons in the basis states, whose number is exponential in the number of coupled qubits. Simulation of a neural network called a quantum reservoir, implemented on a small number of qubits, showed that this quantum neural network can solve certain learning tasks with fewer neurons than an equivalent classical reservoir.In this work, in order to obtain an even larger number of basis states, we use quantum oscillators instead of qubits. To go towards an experimental realization, we simulate a reservoir neural network implemented on a Josephson parametric converter, a well known quantum superconducting circuit. This circuit couples two superconducting oscillators through a three-wave-mixing interaction, implemented using a ring of four Josephson junctions. We encode the input data in the resonant oscillators' drives and numerically integrate quantum master equation to find the occupation probabilities of a subset of basis states that represent neural network outputs. We show that this system of two coupled quantum oscillators can solve a benchmark task of sine and square waveform classification, that otherwise requires 25 classical oscillators. Furthermore, in order to test its memory, we train this network to perform chaotic time series prediction and show that with typical experimental parameters for a Josephson parametric converter we obtain performance comparable to a neural network implemented on 30 classical oscillators. These results show that a simple and well known quantum circuit can realize non-trivial machine learning tasks when its dynamics is exploited. Neuromorphic computing thus promises to leverage the full computing capabilities of even small quantum systems. These simulations will guide experimental realization of a reservoir neural network on the Josephson parametric converter.

Mots-Clés: quantum neural networks, superconducting circuits, Josephson parametric converter

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Determination of the disorder potential from quantum transport data using machine learning methods

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We present a machine learning approach that allows to characterize the disorder potential of a two-dimensional electronic system from the partial local density of states (PLDOS). Since the PLDOS is fast to compute, we simulated the latter for a large number of disorder configurations in order to train the neural networks. We show that the trained networks are able to recognize details of the disorder potential of an unknown sample from the PLDOS of the electrons, and that they can even reconstruct the complete potential landscape seen by the electrons [1]. In order to determine the disorder potential of a real sample from experimental transport measurements, we are currently working on the recognition of the potential from scanning gate spectroscopy (SGM) data. This objective is more challenging due to the considerably larger amount of time required to compute the SGM response. This constraint implies to train the neural network with just a few examples. However, using machine-learning techniques, encouraging preliminary results indicate that such a characterization of the potential from the SGM response is possible.

[1] G. J. Percebois and D. Weinmann Phys. Rev. B **104**, 075422 (2021)

Mots-Clés: Quantum transport, Disorder, Machine learning

*Intervenant

Engineering a U(1) lattice gauge theory in classical electric circuits

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Lattice gauge theories are fundamental to such distinct fields as particle physics, condensed matter, and quantum information science. Their local symmetries enforce the charge conservation observed in the laws of physics. Impressive experimental progress has demonstrated that they can be engineered in table-top experiments using synthetic quantum systems. However, the challenges posed by the scalability of such lattice gauge simulators are pressing, thereby making the exploration of different experimental setups desirable. Here, we realize a $U(1)$ lattice gauge theory with five matter sites and four gauge links in classical electric circuits employing nonlinear elements connecting LC oscillators. This allows for probing previously inaccessible spectral and transport properties in a multi-site system. We directly observe Gauss's law, known from electrodynamics, and the emergence of long-range interactions between massive particles in full agreement with theoretical predictions. Our work paves the way for investigations of increasingly complex gauge theories on table-top classical setups, and demonstrates the precise control of nonlinear effects within metamaterial devices.

Mots-Clés: metamaterials, lattice gauge theory

*Intervenant

Coulomb interactions and effective quantum inertia of charge carriers in a macroscopic conductor

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On one hand, electrical transport across macroscopic conductors can be described in terms of lumped circuit elements, including inductances and capacitances which can be computed from the electromagnetic field generated by charges and current within the conductor. On the other hand, the linear response of ballistic quantum conductors can also be described in terms of inductances and capacitances of quantum origin reflecting the fermionic nature of charge carriers which leads to characteristic RC or LC time scales associated with ballistic times of flights [1-2]. In the present work, we demonstrate that macroscopic conductors involving a small number of conducting channels also exhibit linear response properties of quantum origin, combining the effects of the Pauli principle and of Coulomb interactions, even if their size is much larger than the electronic coherence length.

As a paradigmatic example, we study the low-frequency admittance of a quantum Hall bar of a size much larger than the electronic coherence length [3]. We find that this macroscopic conductor behaves as an ideal quantum conductor with vanishing longitudinal resistance and purely inductive behavior up to 1 MHz. Using several measurement configurations, we study the dependence of this inductance on the length of the edge channel and on the integer quantum Hall filling factor. The experimental data are well described by a scattering model for edge magneto-plasmons taking into account the effective long range Coulomb interactions within the sample. We find that the inductance's dependence on the filling factor arises predominantly from the effective quantum inertia of charge carriers induced by Coulomb interactions.

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and M. B́uttiker, Phys. Rev. Lett. **98**, 166806 (2007)

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Mots-Clés: quantum inductance / plasmons / quantum Hall effect

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1	Radiofrequency magneto-transport in a mesoscopic Hall bar	Altimiras Carles
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4	Towards a versatile and resilient detection of paramagnetic species at the micron scale using quantum circuits techniques	Bahr Arne
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11	Evidence of Orbital paramagnetism in a graphene/BN moiré	Ferrier Meydi
12	Circuit QED implementation of quantum impurity models	Florens Serge
13	Kondo-cloud extension around quantum dots	Fossion Diego
14	Non parametric photon conversion in circuit-QED	Fraudet Dorian
15	Combined Dissipative and Hamiltonian Cat Qubit Confinement	Gautier Ronan
16	Shot noise investigation of anyonic statistics in the Fractional Quantum Hall regime	Glidic Pierre
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23	Cavity-photon induced state transitions in a Fluxonium qubit	Jouan Alexis
24	Signatures of Liouvillian Exceptional Points in a Quantum Thermal Machine	Khandelwal Shishir

#	Titre	Auteur
25	Predicting the spatial separation between valley channels in a quantum Hall graphene PN junction : a self-consistent quantum electrostatic approach	Lacerda Santos Neto Antonio
26	Non-equilibrated to fully equilibrated edge heat transport in hole-conjugate states of the fractional quantum Hall effect	Le Breton Gaëlle
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30	Fractionalization and anyonic statistics in the integer quantum Hall regime	Mora Christophe
31	Proposal for a NanoMechanical Qubit	Pistolesi Fabio
32	1D microwave photonic crystals for on-chip signal processing	Praquin Matthieu
33	Suppression of the radiation squeezing in interacting quantum Hall edge channels.	Rebora Giacomo
34	Engineering superconductivity with crystal orientation in SrTiO3-based 2DEG: superfluid stiffness of the (001), (110) and (111) interfaces	Saïz Guilhem
35	When topology and electronic correlations meet: BCS superconductivity and the Berry curvature	Simon Florian
36	Probing quantum electromagnetic magnetic fields with subnanosecond time resolution: the single electron radar	Souquet-Basiège Hubert
37	Identifying and characterizing quantum skyrmions	Stepanov Evgeny
38	Superconductor/Semiconductor hybrid nanostructures based on Germanium for quantum information	Tangchingchai Chotivut
39	A three-dimensional chiral Veselago lens	Tchoumakov Sergueï
40	Robust propagating in-gap modes due to spin-orbit domain walls in graphene	Touchais Jean-Baptiste
41	Anisotropy of Yu-Shiba-Rusinov states	Uldemolins Mateo
42	Electronic properties of 2D superconducting BSCCO flakes	Velluire Pellat Zoe
43	Specific heat of a 2D electrons gas in Quantum Hall regime	Veyrat De Lachenal Lou-Anne
44	Superconducting resonators for fast readout of Si spin qubits	Vincent Estelle
45	Bloch oscillations in Josephson Junctions	Wagner Alexander
46	Spontaneous orbital magnetization of mesoscopic dipole dimers	Weick Guillaume
47	Asymmetric power dissipation in electronic transport through a quantum point contact	Weinmann Dietmar
48	Optimizing the energy consumption of the full-stack of a quantum computer	Whitney Robert
49	Si hole qubits in a cQED architecture	Yu Cécile

Program at a glance

LUNDI 29

- Lunch
- J. Cayssol
- C. Avogadri
- L. Jezequel
- Coffee break
- P. Simon
- F. Massee
- M. R. Sahu
- N. Leumer
- Free time
- Dinner
- Poster session

MARDI 30

- C. Mora
- A. Assouline
- Coffee break
- D. Ferraro
- O. Maillet
- Lunch
- E. Collin
- S. Léger
- A. Anthore
- I. Safi
- Coffee break
- J. Basset
- N. Paradiso
- T. Charpentier
- X. Ballu
- Free time
- Dinner
- Poster session

MERCREDI 1

- J. F. Roch
- E. Flurin
- T. Allard
- Coffee break
- X. Waintal
- Q. Ficheux
- Lunch
- Free time
- G. Haack
- J. Wise
- C. Groth
- In Memoriam
- Dinner
- Free time

JEUDI 2

- M. Filippone
- D. Markovic
- G. Percebois
- Coffee break
- H. Riechert
- C. Chaubet
- Lunch

9 10 11 12 13 14 15 16 17 18 19 20 21 22