# Quantum Mesoscopic Physics

## March 25th - April 1st, 2023

# Abstract Booklet Posters

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# Channel mixing in a quantum Hall two-particle interferometer

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We consider a two-particle interferometer in the quantum Hall regime, where voltage sources applied to ohmic contacts inject electronic excitations into a pair of copropagating edge channels and are sent to collide at a quantum point contact. Current fluctuations at the output of the interferometer have been shown to be a very useful tool to probe the quantum statistics and indistinguishability of the injected excitations. For an ideal scenario, the noise is completely suppressed when the incoming excitations are synchronized. However, recent experiments [1] performed in the integer quantum Hall regime at filling factor 2 have observed an incomplete reduction of the noise. In contrast to other injection schemes, this experiment cannot be explained by Coulomb interactions. Here, we analyze the impact of channel mixing due to inter-edge tunneling on the current noise measured at the output of the interferometer. We show that this mixing can be responsible for an incomplete suppression of the noise, thereby reducing the visibility of the interference [2]. Our model provides a good quantitative agreement with the experimental data. Similar features in the noise are observed at filling factor 2/5, which suggest that channel mixing may play a relevant role in the fractional quantum Hall regime, too.

[1] I. Taktak, M. Kapfer, J. Nath, P. Roulleau, M. Acciai, J. Splettstoesser, I. Farrer, D. A. Ritchie, and D. C. Glattli, Nat. Commun. 13, 5863 (2022)
[2] M. Acciai, P. Roulleau, I. Taktak, D. C. Glattli, and J. Splettstoesser, Phys. Rev. B 105, 125415 (2022)

# Microwave Photon to Electron Conversion using a High Kinetic Inductance Superconducting Circuit

**Julien Basset**
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We use granular aluminum to build a high impedance microwave resonator strongly coupled to a hybrid single electron transistor (SINIS based SET). The engineered Fabry-Perot cavity has a large bandwidth set by the finite impedance mismatch on one side and by the transistor on the other. By adjusting the dc-voltage bias and the gate voltage applied to the SET, we tune the photon to electron conversion rate up to a point where it matches the microwave coupling rate of the resonator on the other side. At this critical coupling, microwave photons are efficiently and continuously converted into a flow of electrons across the SET. Remarkably, the quantum efficiency estimated from the measured photo-assisted current approaches unity.



# Levitons in superconductors

**Bruno Bertin-Johannet**
*Centre de Physique Théorique*

The aim of this talk is to introduce the topic of Levitons physics in hybrid systems involving normal or half metals and BCS superconductors. Leviton physics is a subtopic of Electron Quantum Optics (EQO), which aims at finding, describing and using electronic systems which allow transport of single electronic excitations. The parallel with quantum optics is striking, photon source are replaced by electron source: periodically driven systems of electrons, beam splitters are replaced with quantum point contacts and intensity correlations are replaced by electronic current noise. The principal complications are that the statistic of electrons is fermionic and that they interact via the Coulomb force, isolating a single electron therefore requires a modification of the paradigm of quantum optics. It was shown by Levitov and coworkers, that a time-dependent voltage drive made of integer Lorentzian periodic pulses create excitations that propagate above the Fermi sea without unwanted electron hole excitations. These excitations, called Levitons, were experimentally realised ten years ago, and seem to be ideal candidate for electrons quantum optics. Remarkably, they were involved in the main extensions of paramount quantum optics effects, such as the Hong-Ou Mandel or Hanburry-Brown and Twiss experiments. Notably, in the nanophyics team of the Centre de Physique Théorique, this paradigm has been extended to correlated states of matter, such as the Franctional Quantum Hall Effect (FQHE). One of the most promising ambitions of this extension would be the manipulation of isolated anyons. In this talk I will discuss our involvment in another extension of this paradigm to correlated systems, BCS superconductors.

I will start by describing the basics of transport through a Quantum point contact and its characterisation through current and noise computations, cite{martin2005}.
Then I will briefly explain how this can be used for EQO in the context of normal metals, where the Fermi liquid picture applies.

I will recall the main results on DC electric current through a QPC between a normal metal and a superconductor, the focus will be on the regime where Andreev reflection dominates. Next, I will describe the link between AR in standard N-BCS junctions and Crossed Andreev Reflection CAR in junctions involving two half metals and a BCS superconductor. The last step of this introductory material is to summarize the aspects of the Floquet formalism, which allow to understand time dependent photo-assisted transport. Rather than proposing an in-depth description of the formalism involved, based on Keldysh Green functions, I will move on to the recent results of the team related to the possibilities for minimal excitations transport in N-BCS junction. Namely I will explain how can half integer Lorentzian pulses of opposite spins combine into a minimal excitation state of Cooper pairs and what are the requirements on the electron sources to achieve this. I will then describe the possibility to use this junction as an on-demand source of Cooper pairs and the required setup. The reverse situation is also intereresting, how can minimal excitations of Cooper pairs be split in opposite spin excitations, are they standard Levitons. Can it be done so as to create entengled states of Levitons, which could be used in Quantum information setup ?

# The fermio-bosonic qubit

**Joan Joel Caceres Ramirez**
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We propose a novel superconducting circuit aiming at more robust quantum states, and featuring two distinct quantum degrees of freedom. It consists in the parallel combination of a large inductance, a capacitor and a quasi-ballistic single-channel weak link. The large inductance results in large fluctuations of the phase across the weak link. The weak link implements a Josephson coupling that depends on an internal fermionic degree of freedom associated with the Andreev level. The electromagnetic modes of the circuit depend on the fermionic occupation, leading to a «»fermio-bosonic»» qubit. We present preliminary calculations of the wave functions, the relaxation and dephasing rates due to noise in the external flux and weak link channel reflectivity. We find that in addition to having little dispersion and disjoint supports, the small energy difference between the states leads to a reduced effect of ohmic bathes on the relaxation indicating very promising coherent properties.



# Gate Tunable Josephson Diode in Proximitized InAs Supercurrent Interferometers

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Carlo Ciaccia(1), Roy Haller(1), Asbjørn C. C. Drachmann(2), Constantin Schrade(2), Tyler Lindemann(3), Michael J. Manfra(3, 4,5, 6, 7) and Christian Schönenberger(1, 8)

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The Josephson Diode (JD) is a non-reciprocal circuit element that supports a larger critical current in one direction than in the other. This effect has been gaining a growing interest because of promising applications in superconducting electronic circuits with low power consumption.

Some recent implementations of a JD rely on breaking of the inversion symmetry of individual Josephson Junctions (JJs). But a recent theoretical proposal has suggested that the effect can also be obtained by combining two inversion symmetric JJs, hosting highly transmitting Andreev bound states, in a Superconducting Quantum Interference Device (SQUID) at a small, but finite flux bias in order to break time-reversal symmetry [1].

We realize a SQUID with two JJs fabricated in a proximitized InAs two-dimensional electron gas. These junctions have been shown to have a high-harmonic content in their Current Phase Relation (CPR) [2]. We show gate control of the diode efficiency from zero up to around 30% at different flux bias. According to [1] the JD efficiency can further be increased, up to 100%, when many more gate-tunable JJs are used in parallel.

We further present preliminary indications that when the interferometer is biased by a half- quantum of applied flux, and the two JJs are tuned to have the same transparencies, current through the SQUID is dominated by pairs of Cooper pairs, while tunnelling of single Cooper pairs is suppressed. It has been shown that the relaxation of a gatemon qubit can be suppressed tenfold by tuning into this parity protected regime [3]. Also, parity protection has been proposed as the building block of several device architectures and gate schemes aimed at improving the coherence and relaxation time of superconducting qubits[4, 5].

[1] Rubèn Seoane Souto, Martin Leijnse, and Constantin Schrade. Josephson diode effect in supercurrent interferometers. Phys. Rev. Lett., 129:267702, Dec 2022.
[2] F. Nichele, E. Portolès, A. Fornieri, A. M. Whiticar, A. C. C. Drachmann, S. Gronin, T. Wang, G. C. Gardner, C. Thomas, A. T. Hatke, M. J. Manfra, and C. M. Marcus. Relating andreev bound states and supercurrents in hybrid josephson junctions. Phys. Rev. Lett., 124:226801, Jun 2020.
[3] T. W. Larsen, M. E. Gershenson, L. Casparis, A. Kringhøj, N. J. Pearson, R. P. G. Mc- Neil, F. Kuemmeth, P. Krogstrup, K. D. Petersson, and C. M. Marcus. Parity-protected superconductor-semiconductor qubit. Phys. Rev. Lett., 125:056801, Jul 2020.
[4] Andrea Maiani, Morten Kjaergaard, and Constantin Schrade. Entangling transmons with low-frequency protected superconducting qubits. PRX Quantum, 3:030329, Aug 2022.
[5] Constantin Schrade, Charles M. Marcus, and Andr´as Gyenis. Protected hybrid superconduct- ing qubit in an array of gate-tunable josephson interferometers. PRX Quantum, 3:030303, Jul 2022.

# Studying the effect of magnetic fields on a travelling wave parametric amplifier

**Christian Dickel**
*Physics Institute II, University of Cologne*

Travelling wave parametric amplifiers (TWPAs) with their quantum-limited amplification at large bandwidth and high saturation power have become a key technology for superconducting qubits and other quantum technologies using microwave readout. They have been used successfully in several superconductor-semiconductor hybrid experiments where magnetic fields are applied. We provide a more systematic study of how magnetic field affects the TWPA figures of merit (gain, bandwidth, saturation power). While out-of-plane magnetic field produces strongly hysteretic behavior and a strong limitation on performance above 5mT likely due to vortices, for in-plane field, the Josephson junction geometry rather than critical field of aluminum limits the TWPA we study, with one in-plane direction being limited at 2mT while in the other, the gain remains similar up to 60mT. Experiments to investigate the effectiveness of magnetic shielding are ongoing. Our results are both useful for understanding current viability of TWPAs in high-field experiments and show that in-plane field could be a viable tuning knob to shift the gain window down.



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# Finite frequency measurement of the third cumulant of current noise in a tunnel junction

**Clovis Farley**
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We report the first measurement of the third cumulant of current statistics of a mesoscopic device, a tunnel junction, in a fully quantum regime. We have measured the non-zero correlator <i2(f)i(-2f)>, as it allows us to reach a regime where frequency (f=5GHz) is the most relevant energy scale (hf>>eV,kT) for every current fluctuation (i) involved.

The contribution from feedback effects and correlations induced by environmental noise are both accounted for quantitatively. This characterization allows us to demonstrate the direct impact of zero-point fluctuations in a circuit on measured voltage statistics.

The noise susceptibility, the response of the current statistics to a fluctuating voltage, is also measured and corresponds to theoretical predictions.

These results raise the question if it is possible to have a skewed vacuum even when no photons are emitted by the junction.



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# Techniques to assess noise sources in cryogenic measurement platforms

**Matthieu Féchant**
*KIT*

Techniques to assess noise sources in cryogenic measurement platforms are central to advance the performance of superconducting circuits.
In these systems, one of the prominent sources of incoherence is the presence of non-equilibrium quasiparticles.
Using charge sensitive transmons, it has been showed that tunneling of quasiparticules across their junction can couple to the qubit and induce photon loss. [S. Diamond et al. PRX Quantum 3, 040304]
By measuring the power, temperature or spatial dependence of this exchange, it is possible to learn about the sources of quasiparticle losses and find strategies to suppress them.
We have reproduced some of the results in [S. Diamond et al. PRX Quantum 3, 040304] and we aim to use this new detection technique to characterize and quantify noise sources in typical cryogenic setups.



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# A nano-electromechanical quantum simulator

**Sttefan Forstner**
*Institute of Photonic Sciences (ICFO)*

Electron-phonon interactions lead to a plethora of phenomena in strongly correlated solid-state systems such as superconductivity and charge-density waves. However, the complex dynamics manifesting these phases can be beyond the reach of computational modelling, especially when taking into account electron-electron interaction. Therefore, one of the outstanding challenges in the field of correlated-electron physics is a widely tuneable model system that can mutually couple several electronic and phononic degrees of freedom. To date, no such system has been experimentally realized. While previous efforts have mostly focused on cold-atom configurations, nano-electromechanical systems are naturally suited to address this challenge. One of the most challenging requirements to engineering such a system is the achievement of ultrastrong electromechanical coupling, which has been recently demonstrated by our research group in a capacitively coupled carbon nanotube. Leveraging this capability, we work to engineer a model system in which electronic degrees of freedom are defined within four quantum dots and coupled to vibrational modes of a carbon nanotube. If successful, the project will enable the first experimental platform for quantum simulation of electron-phonon coupling.

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# Visualizing the Quantum Capacitance of Strained MoS2 Monolayer by Electrostatic Force Microscopy

**Cinzia Gi Giorgio**
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*Department of Physics E.R. Caianiello, University of Salerno, Fisciano, Italy*

We used radio frequency-assisted electrostatic force microscopy (RF-EFM) to investigate the electric field control of biaxially strained molybdenum disulfide (MoS2) monolayers (MLs), produced via hydrogen (H)-ion irradiation. As a semiconducting member of the two-dimensional transitional metal dichalcogenide family, MoS2 ML has recently attracted significant attention due to its promising opto-electronic properties, further tunable by strain.
Here, we take advantage of the RF assistance to isolate the contribution of atomic scale defects, such as sulfur vacancies or H-passivated sulfur vacancies, to the electrostatic properties of the strained ML, from that of the intrinsic quantum capacitance. Additionally, we pursue a finite frequency ($fRF$ = 300 MHZ) imaging of quantum capacitance, elucidating its spatial variation over a mesoscopic length scale, due to the local modulation of the defect-driven n-type nature of the strained ML. The capability of performing finite frequency capacitance imaging, throughout a non-invasive nanoscale approach, paves the way to use RF-EFM to investigate frequency and spatial-dependent phenomena, such as the electron compressibility in quantum materials, which are yet quite challenging to characterize.



# Heat transfer modelling in the crossover regime between conduction and radiation

**Mauricio Gómez Viloria**
*Laboratoire Charles Fabry*

Fluctuational electrodynamics (FED) theory describes the near field radiative heat transfer for separation distances below the thermal wavelength (some microns at ambient temperature), where the heat flow between two solids at different temperatures can exceed the far field limit by several orders of magnitude, in particular when the bodies exchanging heat support surface resonant modes, such as surface phonon-polaritons or surface plasmons. At even smaller distances, in the so-called extreme near field (distances in the nanometer range and below) the physics is expected to change radically. Interestingly, two recent scanning thermal microscopy (SThM) experiments, approaching gold tips to gold substrates, reach apparently opposite conclusions. While one of them shows large deviations from FED for separation distances of few nanometers, another experiment shows no deviations from FED even at sub-nanometer gaps, where acoustic phonons and electrons are expected to contribute as further channels to the heat exchange. Here we introduce a theoretical framework to investigate the heat transfer mediated by photons, phonons and electrons between two metallic bodies. We quantify the role of electron tunnelling currents by paying attention to the role played by the shape of the electronic barrier in the presence of electron-electron screening interactions. Using an approach based on the elastic theory, we address the role of acoustic phonons coupled through the Van der Waals and the electrostatic forces. Finally, we employ FED to study the role played by photons, by taking into account the contribution of non-local effects. This theoretical work allows us to outline the relative weight of the different carriers with respect to the separation distance, and to highlight the crucial role played by the external bias voltage on the heat flux carried by the three types of carriers.

Preprint: https://arxiv.org/abs/2212.03073

# Controlling the error mechanism in a tunable-barrier single-electron pump

**Frank Hohls**
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Single-electron pumps based on tunable-barrier quantum dots are the most promising candidates for a direct realization of the unit ampere in the recently revised SI: they are simple to operate and show high precision at high operation frequencies. The current understanding of the residual transfer errors at low temperature is based on the evaluation of backtunneling effects in the decay cascade model. This model predicts a strong dependence on the ratio of the time dependent changes in the quantum dot energy and the tunneling barrier transparency. Here we employ a two-gate operation scheme to verify this prediction and to demonstrate control of the backtunneling error [1]. As experimental model system we use a single-electron pump realized by a quantum dot hosted in a GaAs/AlGaAs heterostructure. We derive and experimentally verify a quantitative prediction for the error suppression, thereby confirming the basic assumptions of the backtunneling (decay cascade) model. Furthermore, we demonstrate a controlled transition from the backtunneling dominated regime into the thermal error regime. The predicted suppression of transfer errors by several orders of magnitude at zero magnetic field was additionally verified by precision measurements.
[1] F. Hohls et al., Phys. Rev. B 105, 205425 (2022), https://doi.org/10.1103/PhysRevB.105.205425



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# Quasiparticle Andreev reflection in the fractional quantum Hall effect

**Kishore Iyer**
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Andreev reflection is the phenomenon of an electron impinging on a normal metal-superconductor junction in the sub-gap regime from the normal metal side, being retro-reflected as a hole, accompanied by the transmission of a Cooper pair into the superconductor. We theoretically study a similar phenomenon occurring in the strongly correlated system of the fractional quantum Hall effect, endowed with two quantum point contacts (QPC.)

The first QPC is tuned to be transparent, and as a result, the back-scattering current consists of a dilute beam of e/m quasiparticles (m -> odd integer.) On the other hand, the second QPC placed downstream of this dilute beam is opaque, effectively breaking the quantum Hall liquid into two, and hence transmits only electrons. The latter process is predicted to be accompanied by a process akin to Andreev reflection where the transmission of electrons is accompanied by the reflection of an (e-e/m) charge [1].

Motivated by the measurement protocol of recent experiments [2], we calculate explicitly the tunneling-current, cross-correlation, and auto-correlation in this two-QPC geometry, which contains explicit signatures of the Andreev processes. We find our theoretical calculations to have a clear match with the experimental data.

[1] C. L. Kane and Matthew P. A. Fisher. "Shot noise and the transmission of dilute Laughlin quasiparticles". In: Phys. Rev. B 67 (4 Jan. 2003), p. 045307. doi: 10.1103/PhysRevB.67.045307. url: https://link.aps.org/doi/10.1103/PhysRevB.67.045307.

[2] P. Glidic et al. Quasiparticle Andreev scattering in the =1/3 fractional quantum Hall regime. 2022. doi: 10.48550/ARXIV.2206.08068. url: https://arxiv.org/abs/2206.08068.

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# Topological Josephson Trijunctions: Majorana Source and Path

**Kyungtae Kim**
*KAIST*

We consider a topological Josephson trijunction on two dimension in a perpendicular magnetic field, which hosts mobile Majorana bound states (MBSs). We predict that the trijunction behaves as either a source/sink or a path of MBSs. As its superconducting phases change, MBSs are pairwise generated or annihilated at the trijunction center in the source/sink mode, while an MBS passes the center in the path mode. The two modes need to be applied appropriately, to braid or fuse MBSs in trijunction networks. For illustration, we propose a double trijunction. It can exhibit non-Abelian state evolutions and Josephson currents of nontrivial periods, when at least one of its two trijunctions is in the source/sink mode. The nontrivial periods are identified by fractional shifts of Shapiro spikes. By contrast, only trivial $2 pi$ periodic Josephson currents occur, when both the trijunctions are in the path mode.



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# Pseudogap Kondo Entanglement

**Minsoo Kim**
*KAIST*

The pseudogap Kondo model, in which a magnetic impurity is screened by conduction electrons of pseudogap density of states, has been used to study the Kondo destruction quantum critical point and the magnetic impurity on graphene. We study quantum entanglement and Kondo clouds of the pseudogap Kondo model. Using the numerical renormalization group method, we study the temperature and spatial dependences of the entanglement between the impurity and conduction electrons. We find that in the low energy regime, the dependences show universal power-law scaling behavior. The power-law exponents depend on the different phases of the model. We explain the universal behavior by developing a fixed-point analysis method combined with impurity operators. Our analysis provides a systematic way of studying the entanglement in general impurity models which have energy dependent density of states.



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# Electrical characterization of Ge/SiGe semiconductor heterostructures

**Elyjah Kiyooka**
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KIYOOKA Elyjah, TRONCOSO FERNANDEZ-BADA Gonzalo, TANGCHINGCHAI Chotivut, BRUN-BARRIERE Boris, SCHMITT Vivien, ZIHLMANN Simon, LEFLOCH Francois, MAURAND Romain, HOUZET Manuel, HARTMANN Jean-Michel, DE FRANCESCHI Silvano
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Ge quantum wells in SiGe heterostructures are a promising new platform for a new generation of quantum devices due to their high mobility [1], ability to be proximitized by superconductors and compatibility with standard Si CMOS fabrication technology among other advantages [2]. They have shown rapid progress as both spin qubits [3] and as superconducting devices [4]. In this poster, I will show the electrical characterization of Ge/SiGe semiconductor heterostructures by means of magneto-transport measurements of the mobility, carrier density, and effective mass. I will also report on the quality of the superconductor-semiconductor interface in Josephson field-effect transistors, quantifying the IcRn product and the excess current, and providing evidence of multiple Andreev reflection.

[1] Giordano Scappucci et al. The germanium quantum information route. Nature Reviews Materials, pages 1–26, 2020.
[2] Amir Sammak et al. Shallow and Undoped Germanium QuantumWells: A Playground for Spin and Hybrid Quantum Technology. Advanced Functional Materials, 29(14), 2019.
[3] Nico W. Hendrickx et al. A four-qubit germanium quantum processor. Nature, 591(7851):580–585, 2021.
[4] Vigneau, F. et al. Germanium Quantum-Well Josephson Field-Effect Transistors and Interferometers. Nano Letters, 19(2), 1023–1027, 2019.



# QPS induced drag effect in a system of capacitively coupled superconducting nanowi

**Aleksandr Latyshev**
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In the present work we investigated the interplay between quantum phase slips (QPS) phenomena and transport properties in a system of two electromagnetically coupled ultrathin superconducting wires. It was demonstrated that the QPS phenomena in one of two coupled wires can generate voltage fluctuations in both characterized by a dynamics of the corresponding voltage pulses propagating in the first and second wires. We have shown that in such structures there exist two plasma modes propagating with different velocities along the wires. We have explicitly evaluated these velocities and demonstrated that these plasma modes are the same for both wires forming a single effective dissipative quantum environment interacting with electrons inside the structure [1]. Our results have significant implications for the low-temperature transport properties of coupled superconducting nanowires. In particular this result clearly illustrates specific features of voltage fluctuations induced in the second wire by a QPS event in the first wire: Such fluctuations are characterized by zero average voltage and non-vanishing voltage noise [2]. It was shown that the drag effect or in other words the presence of finite average voltage in the second wire caused by a transport current in the first significantly depends on the non-linearity in the system. The non-linearity is necessary to create the asymmetry between Mooij-Schon modes propagating in opposite directions in order to obtain finite contributions on the voltage contacts. Assuming the possibility of topological QPS configurations occurring in the both wires one obtains the required non-linearity action of QPS in the second wire on induced plasmonic modes. The effect of interaction between QPS anti-QPS in different wires leads to a modification of power law dependence of drag voltage.

1.Latyshev A., Semenov A. G., Zaikin A. D. Plasma modes in capacitively coupled superconducting nanowires //Beilstein Journal of Nanotechnology. – 2022. – T. 13. – No. 1. –C. 292-297.
2.Latyshev A., Semenov A. G., Zaikin A. D. Voltage fluctuations in a system of capacitivelycoupled superconducting nanowires // Journal of Superconductivity and Novel Magnetism. –2020. – T. 33. – No. 8. – C. 2329-2334

# CMOS compatible Josephson Field Effect transistor

**Axel Leblanc**
*Lateqs-Pheliqs-CEA Grenoble*

Superconducting qubits is nowadays the most advanced platform for quantum computing but the scalability of these circuits remains one of the main challenges. In order to address this question, the integrability of these technologies into classical electronics processes is a key point. This work focuses on a CMOS compatible way to build a superconducting qubit. A promising approach seems to be the gatemon geometry in which the JoFET is a classical MOSFET with superconducting source and drain. Silicides (CoSi2, V3Si, PtSi) [1] as well as superconducting boron doped silicon and strained germanium quantum well [2] are good candidates for this purpose. This system should take advantages of years of classical microelectronics development as well as recent breakthroughs in superconducting quantum circuits.



# Quantum emission of photon multiplets by a dc-biased superconducting circuit

**Gerbold Ménard**
*LPENS*

In nature the emission of photon from electronic relaxation is a well known phenomenon. The rate at which this process happens is controlled by the fine structure constant $\alpha=1/137$. Because of this small value, the emission of more than one photon from a single relaxation event is a very rare event in nature and in optical experiments. In order to increase the probability of emission of photon multiplets it is necessary to increase the light-matter coupling intensity which can be done in the context of circuit QED by properly designing an RF resonator. I will discuss here the result obtained on a device with a coupling factor $\alpha\approx2$ [1]. By biasing a SQUID in series with a microwave resonator with a strong inductance coil we observe the emission of k photons for dc voltages V_dc=khν/2e which allows us to witness the emission of photon multiplets up to k=6. In order to investigate the statistic of the emission we compute the Fano factor from measurements of a second order correlator and find that for small enough Josephson energies the Fano factor coincides with k. We also perform a theoretical analysis of our system in order to understand the role of the bias noise as well as the detuning from the resonance condition and find an excellent agreement between theory and experiment.

[1] C. Rolland et al. Phys. Rev. Lett. 122, 186804 (2019)

# Breathing modes: quantum magnetic lens effect and Bloch oscillations in twisted bilayer graphene

**Dmytro Oriekhov**
*Instituut-Lorentz for Theoretical Physics, Leiden University*

We consider the propagation of electrons in a lattice with an anisotropic dispersion in the x-y plane (lattice constant a), such that it supports open orbits along the x axis in an out-of-plane magnetic field B. We show that a point source excites a «breathing mode“, a state that periodically spreads out and refocuses after having propagated over a distance l=(e a B/h)^(-1) in the x direction. Unlike known magnetic focusing effects, governed by the classical cyclotron radius, this is an intrinsically quantum mechanical effect with a focal length $\propto\hbar$. In addition, we show that similar effect appears in the network model of minimally twisted bilayer graphene due to random-walk-type physics of quasiparticles and gives rise to effective Bloch oscillations. Such Bloch oscillations result in the oscillations of magnetoconductance and can be captured in modern transport experiments.



# Josephson two-tone spectroscopy in the EHF band

**Ambroise Peugeot**
*ENS Lyon*

We have developed a novel two-tone spectrometer able to detect resonances of mesoscopic quantum systems up to unprecedented high frequencies ( ~100 GHz). We use a voltage-biased Nb Josephson junction as an on-chip source of high-frequency radiation to irradiate the System-of-Interest (SoI). Contrary to previous experiments (1)(2) where the absorption of energy by the SoI was detected by measuring the dc current through the junction, in our work we directly detect the excitation of the SoI through the dispersive shift of a coupled superconducting resonator. This simplifies the operation of our spectrometer as the detection part is separated from the excitation. We also benefit from the superior sensitivity of the high quality factor cavity. Our spectrometer could be used to e.g. study the Andreev bounds states located in hybrid superconducting nanostructures (3) without destroying their quantum coherence.

(1) Bretheau, L., et al. "Exciting Andreev pairs in a superconducting atomic contact." Nature 499.7458 (2013): 312-315
(2) Griesmar, J., et al. "Superconducting on-chip spectrometer for mesoscopic quantum systems." Physical Review Research 3.4 (2021): 043078
(3) Pillet, J. D., et al. "Andreev bound states in supercurrent-carrying carbon nanotubes revealed." Nature Physics 6.12 (2010): 965-969

# Nonlocal Josephson effect in carbon nanotubes

**Jean-Damien Pillet**
*LPMC, École Polytechnique, IP Paris*

An Andreev molecule is an artificial quantum system composed of two Josephson junctions very close to each other. The latter couple thanks to the overlap of their Andreev states which hybridize into a molecular state. A striking consequence of this coupling is that the supercurrent flowing through one junction does not only depend on the superconducting phase difference across it but also on that across the other junction [1]. This effect is called nonlocal Josephson effect. We have realized such an Andreev molecule in a device composed of a single metallic carbon nanotube connected to three superconducting electrodes. In this structure, we observe that the critical current of one junction depends on the superconducting phase difference across the other junction which we control with a magnetic flux. Such a phenomenon is a signature of the nonlocal Josephson effect. In order to understand how the hybridization of the Andreev states occurs at the microscopic scale, we have explored the dependence of the nonlocal Josephson effect on the chemical potential of the carbon nanotube, which we control with a backgate voltage. This reveals that the quantization of the electronic states of the nanotube into discrete energy levels plays a major role in the hybridization of Andreev states. This non-local Josepshon effect could be exploited to develop protection mechanisms against relaxation for Andreev qubits or to create more elaborate non-local electronic states, as in an Andreev polyacetylene.

[1] J.-D. Pillet et al., Nano Lett. 19, 7138 (2019).



# Phase resolved photo-assisted quantum noise

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Photo-assisted noise in mesoscopic devices, i.e. the effect of an ac excitation on the current-current correlator in a phase-coherent conductor, has attracted a long lasting, both experimental and theoretical interest, The effect of a time-dependent voltage V(t) of various shape (sinusoidal, bi-harmonic, Lorentzian, etc.) at frequency F has been observed on the finite frequency noise at another frequency f, i.e. <I(-f)I(f)> in various quantum systems (tunnel junction, diffusive wire, quantum point contact, etc.) and interpreted in terms of photo-assisted noise as well as electron quantum optics or quantum tomography of electronic signals. The same ac excitation has been shown to induce correlations between currents at different frequencies, captured by the noise susceptibilities <I(f)I(nF-f)> with n integer, leading to the generation of squeezed vacuum in the microwave domain. All these experiments can be accounted for by a simple formula which is enlightening in time-domain: <I(t)I(t')> simply involves its equilibrium value, which depends only on t-t', and the flux (i.e. the integral of eV(t)/h over time) between t and t'. In particular, what happened before t is irrelevant. This formula has never been experimentally checked for a time-dependent voltage. Here we provide the time-domain measurement of current-current correlators synchronously with an ac sinusoidal excitation at frequency 4GHz. This allows us to explore correlations in current fluctuations inside a single excitation period, to define phase-dependent noise and deduce noise susceptibilities and time/frequency Wigner functions, all in agreement with theory.

# Crossed Andreev reflection in spin-polarized chiral edge states due to the Meissner effect

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Abstract: Crossed Andreev reflection is a process of converting an electron into a hole while it is transferred from a normal lead to another one through a superconductor. This mechanism induces non-local correlations between two spatially-separated normal leads which can be exploited in different applications related to quantum information processing. In hybrid systems where quantum Hall effect and superconducting correlations are present, crossed Andreev reflection is especially promising in relation to topological quantum computation. In particular, quantum Hall effect edge states at integer filling factor, proximitized via crossed Andreev processes, are predicted to host Majorana bound states. As long as s-wave superconductors are considered, crossed Andreev reflection can be induced only if spin polarization of these edge states is broken. Previous proposals to induce the required spin-tilting were based on materials with strong spin-orbit interaction either in the 2DEG or in the superconductor.

In this work, we unveil a new mechanism to break the spin-polarization in edge states and induce crossed Andreev reflection in the system, without the requirement for spin-orbit interaction or other intrinsic magnetic properties. We consider a superconducting finger with oblique profile wedged into a two-dimensional electron gas, in analogy with the state-of-the-art setup realized in a recent experiment. A perpendicular magnetic field tunes the electron gas into the quantum Hall regime. Due to the Meissner effect, the superconductor distorts the magnetic field lines close to the interface with the quantum Hall phase. This gives rise to an in-plane component of the magnetic field that enables non-local crossed Andreev reflection. Transport properties of this setup are computed numerically by means of the recursive Green's function method. We show that a negative resistance exists as consequence of non-local Andreev processes. We also obtain numerically the zero-energy local density of states, which systematically shows peaks stable to disorder. The latter result is compatible with the emergence of Majorana bound states.



# Revisting minimal excitations in non-linear conductors

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Lorentzian shaped voltage pulses can generate on-demand minimal electronic excitations, («Levitons») without a cloud of neutral electron-hole pair excitations [1,2]. Nonetheless, we show that their characterization is inappropriate for non-linear conductors or quantum circuits [3,4,5].

For that, we use unifying non-equilibrium fluctuation relations (FRs) which generalize Tien-Gordon theory for photo-assisted noise (PASN). These FRs have been checked and exploited experimentally [6]. They provide in particular robust methods for the determination of the fractional charge within the fractional quantum Hall effect (FQHE) [7,8].

Characterization of « Levitons » is based on a theorem 1 stating that PASN is always minimized by its value in the DC regime. We first show that this theorem is restricted to linear conductors. We address the example of a SIS junction where we show that the noise can be reduced by an additional ac voltage. Then we show that for arbitrary time-dependent forces (including gate voltages), and in non-linear conductors, PASN is super-poissonian, and that it reaches the poissonian limit for lorentzian pulses [3].

Specifying to hierarchy states in the FQHE, we show that the injected charge is different both from the electron charge and the fractional charge. We also revisit the approach of the collisional noise in a Hong-Ou-Mandel type geometry, expected to reveal statistics, and address it in particular for lorentzian pulses.

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# Performance of high impedance resonators in dirty dielectric environments

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«Circuit quantum electrodynamics (circuit QED) has emerged as a promising approach for scalable quantum architecture in recent times [1] [2]. A large spin-photon coupling can be achieved through a tunable spin-orbit interaction (SOI) either intrinsically present in quantum dots (QDs) defined in nanowires or induced through the Rashba effect [3]. A prerequisite are QDs with low charge noise, since charge noise results in spin noise through the SOI, limiting the coherence. It is known that dielectrics used to isolate gate lines are a source of charge noise. This noise may also appear on a long time scale and is observed in the form of random gate jumps. If these gate jumps are too large, a particular charge state may be lost,»»kicking»» the qubit out of its computational space. It is therefore paramount to optimize all dielectrics in the vicinity of the nanowire.

In the current work, we optimize the dielectric layers for gate defined quantum dots in Ge/Si core/shell nanowires coupled to a high impedance NbTiN resonator. We compare the resonators on different substrates (Si/SiO2) with different Atomic Layer Deposition (ALD) dielectrics on top. We study the dependence of the resonator quality factors on applied power, temperature, in-plane and out-of-plane magnetic field. Additionally, we perform a noise characterisation and the unloading of the resonators in the time domain. The optimal dielectric sequence simplifies the fabrication process without limiting the performance of the hybrid device.

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# The Galvanic radiation coupler

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The last achievements in electron quantum optics in generating, manipulating and measuring single electron quantum currents pave the way to fast detection of microwave quantum radiations using single electrons. Among the possible probing systems we are studying the electron quantum radar which is a Mach-Zhender Interferometer for single electrons with one of its branches coupled to the external radiation channels to be probed. In this poster I focus my study on the coupling and more specifically on the Galvanic coupler which is a small Ohmic contact coupling the MZI branch to the radiation channels. The Edge Magnetoplasmon scattering matrix of the coupler is constructed using the bosonization formalism and the coupling efficiency is calculated. We demonstrate that the Galvanic coupler is an efficient radiation coupler in a wide frequency band for the detection of quantum radiations.

# The quantum transport states at 2D perovskite and Graphene interface

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Halide Perovskite has been attractive as one of the most promising materials in optoelectrical devices. To improve the devices' efficiency and stability, The incorporation of graphene into perovskite-based optoelectronics has been exploited, in which the graphene acts as transport layers or electrodes and can tune the optical and electrical properties. Despite of a critical part in the graphene and perovskite integration, the states of graphene in this perovskite-centered devices are unclear and rarely researched. Here, quantum transport properties in molecularly thin 2D perovskite/Graphene heterostructure are experimentally investigated by Shubnikov-de Hass (SdH) oscillation in the magneto-resistance. We find strong charge transfer between the perovskite and graphene which induces a hole carrier density in graphene up to ~ 2.79×1013 cm-2. The perovskite layer also lowers the effective mass of graphene from ~0.12 me to ~ 0.08 me. Despite of the efficient charge transfer process, the graphene exhibits the carrier mobility ~550 cm2V-1s-1. The sign of the photo-resistance SdH oscillations corresponds to a reduction of the hole density in graphene under illumination. This heavily dopped graphene implies the possibility of the interaction of carriers and excitons in the van der Waals heterostructure, and higher mobility enables the good performance of perovskite/graphene devices. Our findings unreal the effect of interfacial coupling on the transport properties of graphene imposed by 2D perovskite and give reference for design perovskite optoelectronic devices.



# Coherent control and readout of arsenic dopant spin qubits in silicon

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blished as a promising platform for quantum computing. Silicon can be isotopically purified to provide a nuclear spin-free environment and are very scalable as they benefit from established semiconductor nanofabrication technologies. Phosphorus dopants in silicon have strong coherence times in the order of milliseconds for electron spins and seconds for nuclear spins, the latter of which can act as a quantum memory to store quantum information for longer periods of time.

Arsenic dopants have a non-zero quadruple dipole moment which means that it is possible to transfer information from electron to nuclear spins electrically via electric dipole spin resonance, whereas with phosphorus this must be done with the hyperfine interaction non-electrically. Arsenic dopants also have a I=3/2 nuclear spin manifold, which means that nuclear spins can store quantum information with d = 4 qudit encoding, such that each physical qubit can store two logical qubits of information. Finally, recent developments have demonstrated the atomic-level precision placement of arsenic dopants in silicon, which is more precise than phosphorus dopants which are limited to clusters of dopants. All of these advantages make arsenic a good candidate for a measurement-based entanglement and one-way quantum computing demonstrator. The storage of quantum states in nuclear spins with coherence times in excess of 30 seconds is key to the realisation of a measurement-based quantum computer that relies on an initial resource state such as a cluster state, a highly entangled cluster of qubits that will require sufficient time to grow.

On the other hand, whilst arsenic is expected to have broadly similar coherence times compared to phosphorus, its coherences have not actually been characterised yet. Here, we present our ongoing work to coherently control and readout the spin state in two qubit arsenic dopant devices, as well as reflectometry qubit readout techniques to perform entangling measurements between separate qubits.

# Hybrid Quantum Systems with High-Tc Superconducting Resonators

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Resonators are essential building blocks of microwave circuits and serve a wide variety of functions, from narrow-band filtering to enhancing the interactions between quantum systems and electromagnetic waves. Though fabrication techniques have improved considerably, the performance of resonators remain limited by materials losses. The use of superconductors as the conducting part of resonators significantly reduces dissipation, thus increasing quality factors. So far, most superconducting resonators have been made using low-Tc superconductors (Al, Nb, NbN) through well-established fabrication processes. Their properties have been well characterized and reported, with ultra-high quality factors achieved [1,2]. Still, using high temperature superconductors could be of great interest for the fabrication of resonators and would considerably increase operating ranges of resonators, both thermal and magnetic, while maintaining relatively high quality factors. We have carried out a detailed study of coplanar waveguide resonators made of the high-Tc superconducting cuprate $YBa_2Cu_3O_{7-\delta}$ thin film by varying their coupling capacitors. We show that increasing the capacitive coupling to the external circuit leads to a continuous transition from an undercoupled dissipative regime to a lossless overcoupled one, characterized by a decrease in the resonator quality factor. Our experimental results (resonance frequency, coupling, quality factor, and insertion loss) are in good agreement with the predictions of circuit model theory and the reported results for low-Tc resonators [2]. To assess the potential of $YBa_2Cu_3O_{7-\delta}$ resonators, we used our highest quality factor resonator to perform electron spin resonance on a di(phenyl)-(2,4,6- trinitrophenyl)iminoazanium (DPPH) molecular spin ensemble [3]. The measured spectra reveal a double peak structure characteristic of a Rabi splitting arising from spin-cavity hybridization in a strong cooperative regime. The analysis of the spin-cavity coupling strength, the spin decay rate, and the Landé g- factor indicates an antiferromagnetic transition at low temperatures.

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# Microwave conductivity of 2D superconducting BSCCO flakes

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Two-dimensional superconductors confront physicists with a variety of new challenges by exhibiting a large diversity of exotic electronic phases. The cuprate $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi2212) has a lamellar structure of $CuO_2$ superconducting bilayers separated by $Bi_2O_{2+y}Sr_2O_2$ layers. The unit cell exhibit a cleavage plane due to weak Van der Waals interactions between BiO layers, allowing for the exfoliation and isolation of single superconducting flakes. As the superconductivity of $CuO_2$ planes is two dimensional, Bi2212 single flake makes for an ideal system to study 2D electronic interactions in the different electronic phases. The exploration of this phase diagram has already been performed using chemical doping of samples which also introduces structural changes and disorder, acting on the electronic interactions as well. In this work we report electrostatic doping of Bi2212 flakes to tune the hole density [1]. We have measured the resistivity at different doping level to get more insight on the electronic interactions in the different region of the phase diagram. We will show our first results toward measuring the microwave properties of such a field effect tunable 2D superconducting material.

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# Unconventional transport of Cooper pairs in topological Josephson junctions

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It is well known that Josephson junctions (JJs) in the presence of a perpendicular magnetic field exhibit qualitatively different interference patterns depending on the length of the junction and the current density profile. Two paradigmatic scenarios are the SQUID and the Fraunhofer patterns, corresponding to a current density sharply peaked at the edges of the junction or to a homogeneous current density profile, respectively. In these simple cases the electrons within the Cooper pair (CP) can be treated effectively as a single entity. However, it is not hard to run into physical mechanisms under which this assumption does not hold, leading to new features in the pattern. An example is the even-odd effect in SQUID patterns due to a non-local transmission of CPs, with the two electrons travelling along opposite edges. In fancier JJs, such as in presence of inter-edge tunnelling or broadened edge states, the two electrons can propagate and explore the junction independently. We analyse the consequences of a major role acquired by the single-electron physics in the superconducting context: the relevant flux quantum doubles, introducing unexpected periodicities, and new patterns arise.



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# Gate tunable spin-orbit coupling and superconductivity in KTaO3-based two-dimensional electron gas mesodevices

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The observation of Majorana Zero Modes, motivated by their potential use as a fault-tolerant medium for quantum computation, remains elusive. Superconducting nanowires have concentrated most efforts, but other candidate platforms have been proposed. Oxide quasi two-dimensional electron gases (2DEGs), in particular, gather the three key building blocks for the emergence of topological superconducting states : superconductivity, intrinsic breaking of inversion symmetry, and possibility of coupling with a time-reversal symmetry-breaking source, like a ferromagnetic layer (A. Barthelemy et al., EPL 133 (2021)). The recent discovery of superconductivity in 2DEGs based on quantum paraelectric KTaO3 has revived excitement in the exploration of such physics at oxide interfaces, in line with the works on SrTiO3-based 2DEGs (A. Jouan et al., Nature Electronics 3 (2020)). With a superconducting critical temperature of 2 K and a Rashba spin-orbit coupling significantly larger than SrTiO3's, it sets itself as a promising platform to develop novel electronic devices. However, the fabrication of devices with KTaO3 interfaces proves challenging and the majority of studies are limited to unpatterned samples. Here, we present the fabrication of AlOx/ KTaO3 (111)-based mesodevices and the tuning of superconductivity and spin-orbit coupling by field-effect (H. Witt et al., arXiv:2210.14591 (2022)). Our work could help patterning nanoscale devices to investigate the properties and origin of the superconducting phase at these interfaces.



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# Atomically precise graphene nanoribbons for quantum electronics

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Atomically precise graphene nanoribbons (GNRs) have attracted much interest from researchers worldwide, as they constitute an emerging class of quantum-designed materials, all tailored by controlling their width and edge structure during chemical synthesis. The major challenges toward their exploitation in electronic applications include reliable contacting, complicated by their nanometer size, and the preservation of their intrinsic physical properties upon device integration. Here, we report on the device integration of armchair GNRs into various device architectures with different electrode materials . First, we demonstrate improved tunability of GNRs quantum dot (QD) behavior thanks to the multiple nanometer-sized gates. Second, beyond graphene-based contacts, we demonstrate the successful contacting and characterization of individual GNRs using single-walled carbon nanotubes (SWNT) electrodes and multiple gates. We observe well-defined quantum transport phenomena, including Coulomb blockade, excited states, and Franck-Condon blockade, indicating that a single GNR was contacted. In addition, we demonstrate the encapsulation of GNRs in hexagonal boron-nitride and the contacting using metallic side contacts. These experimental realizations of advanced contracting and gating pave the way for the integration of GNRs in quantum devices to exploit their topologically trivial and non-trivial nature.