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# Abstracts of oral sessions (chronological order)

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# Visualizing out-of-equilibrium superconductivity

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Highly disordered superconductors are predicted to provide non dissipative high impedances in the microwave domain. This makes them very promising materials for the realization of Kinetic Inductance Detectors (KIDs), an infra-red photon sensor. However, previous attempts to use them in KIDs have been hindered by anomalous electrodynamics which could be attributed to an inhomogeneous superconducting state and trapped quasi-particles. During the talk, I will review the experimental inputs of scanning tunneling spectroscopy in highly disordered superconductors in light of their anomalous behavior at high frequency and I will introduce the critical current scanning microcopy, a new experimental technique developed in the laboratory to probe their out-of-equilibrium properties.

# Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry

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Spin-orbit interactions are known to have drastic effects on the band structure of heavy-element-based materials. Celebrated examples are the recently identified 3D and 2D topological insulators. In those systems transport takes place at surfaces or along edges, and spin-momentum locking provides protection against (non-magnetic) impurity scattering, favoring spin-polarized ballistic transport. We have used the measurement of the current phase relation of a micrometer-long single crystal bismuth nanowire connected to superconducting electrodes, to demonstrate that transport occurs ballistically along two edges of this high-spin-orbit material. In addition, we show that a magnetic field can induce to 0-pi transitions and phi0-junction behavior, thanks to the extraordinarily high g-factor and spin orbit coupling in this system, providing a way to manipulate the phase of the supercurrent-carrying edge states.

[1] arXiv:1609.04848

References

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# Pairing of Cooper-Pairs into Quartets and Non-Local Supercurrent in a Three-Terminal Josephson junction

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We report an experimental signature of a new, non-dissipative and nonlocal Josephson current, carried by an Andreev bound state (ABS) connecting three superconducting terminals biased asymmetrically [1]. Aside from the Josephson current made of quartets, sensitive low frequency cross-correlation measurements of current fluctuations in the two biased superconducting contacts prove the origin of the non-local effect [2]. In addition, a rich subharmonic gap structure, which arises from non-local multiple Andreev reflections processes, was observed for the first time [3]. Finally, a biSQID geometry experiment reveals an additional signature for the quartet supercurrent at equilibrium and demonstrates the coherence of the effect.

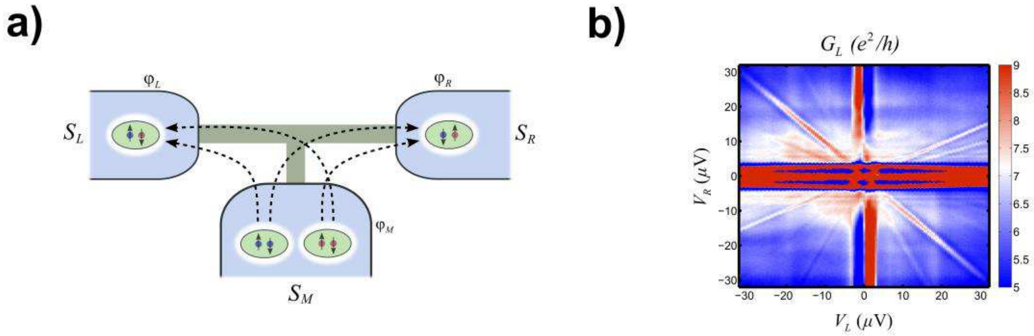


Fig. 1. a) Illustration of the quartet mechanism. b) Differential conductance lines of quartet and sextet.

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# A simple Floquet-Wannier-Stark-Andreev viewpoint and emergence of low-energy scales in a voltage-biased three-terminal Josephson junction

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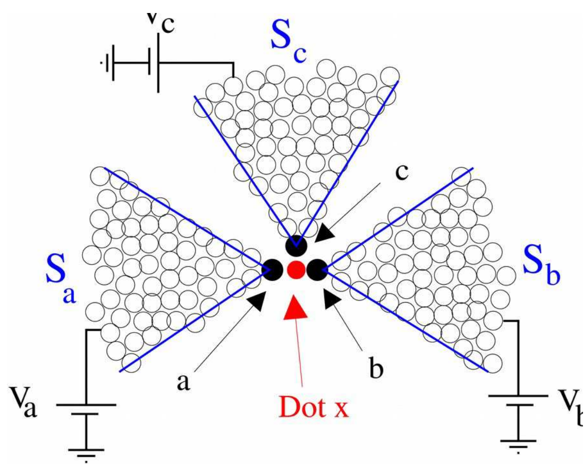



A three-terminal Josephson junction consists of three superconductors coupled coherntly to a small nonsuperconducting island, such as a diffusive metal, a single or double quantum dot. A specific resonant single quantum dot three-terminal Josephson junction (Sa, Sb, Sc) biased with voltages (V, -V, 0) is considered, but the conclusions hold more generally for resonant semi-conducting quantum wire set-ups. A phase-sensitive DC-current due to the quartet or multipair mechanism appears also if V is nonzero. Floquet theory combined with band theory generalizes the equilibrium Andreev bound states (for V=0) to nonequilibrium Floquet-Wannier-Stark-Andreev(FWS-Andreev) ladders of resonances (for nonzero V).

If V=0 and at zero temperature, the supercurrent is related to the phase-derivative of the spectrum of Andreev bound states at negative energy (neglecting the contribution of the continua). If the gap is sent to infinity for nonzero V, then the Josephson relation holds between the current carried by the FWS-Andreev resonances and the phase derivative of the Floquet energy. However, this relation cannot be demonstrated in the presence of strong effect of tiny relaxation (electron-phonon scattering or coupling to the quasiparticle semi-infinite continua by multiple Andreev reflections). In addition, the notion of « states at negative energy » (with V=0) is meaningless for FWS-Andreev resonances (with nonzero V). In practise, if V is nonzero, the relation between spectrum and transport can still be used in a weaker form as a guideline to understand qualitatively the numerical results for the current in the presence of relaxation. Namely, the low-energy scales in the current correlate qualitatively with their counterparts in the FWSAndreev spectrum of resonances, as far as the voltage dependence is concerned. Three important low-energy scales are identified, and a perspective is to relate those low-energy scales to a recent noise cross-correlation experiment [Y. Cohen et al., arXiv:1606.08436].

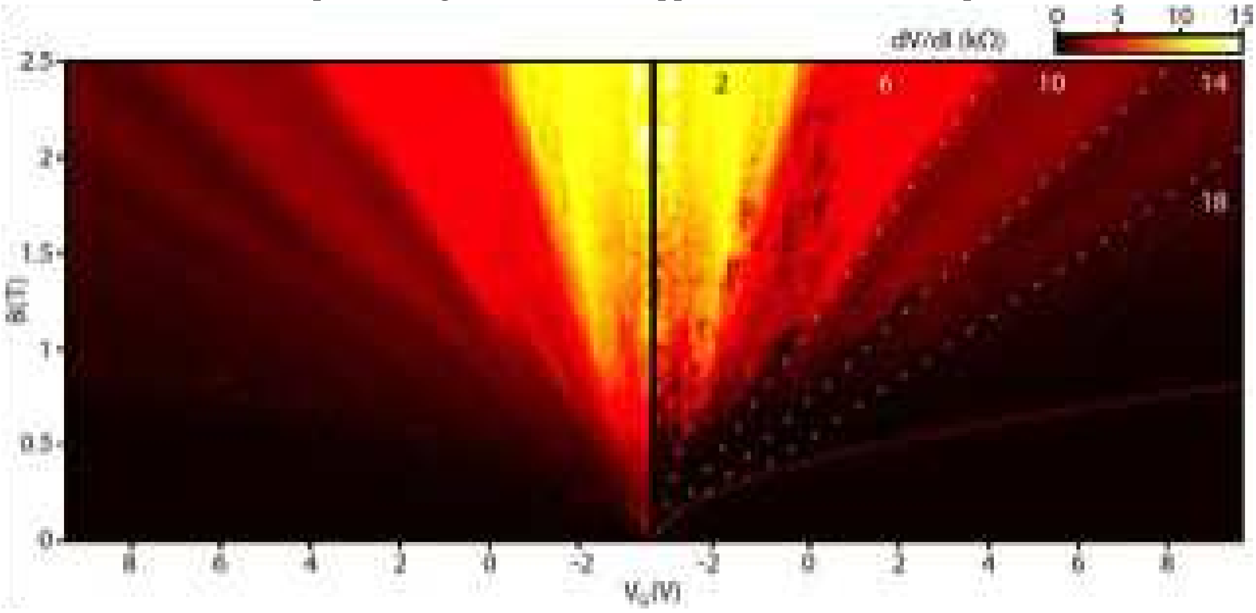
# Supercurrent in the quantum Hall regime

*F. Amet, C.-T. Ke, I. V. Borzenets, J. Wang, K. Watanabe, T. Taniguchi, R. S. Deacon, M. Yamamoto, Y. Bomze, S. Tarucha, and G. Finkelstein*

One of the promising routes towards creating novel topological states and excitations is to combine superconductivity and quantum Hall (QH) effect. It has been predicted that QH chiral edge states can carry supercurrent. However, signatures of superconductivity in the QH regime remain scarce, and a superconducting current through a QH weak link has so far eluded experimental observation. By utilizing high mobility graphene/boron nitride heterostructures we demonstrate the existence of a novel type of supercurrent-carrying states in a QH regime at magnetic fields as high as 2 Tesla.

Ballistic Josephson junctions are made using encapsulated graphene contacted by Mo-Re alloy superconductor with relatively high T_C and H_C2. At low magnetic fields, devices demonstrate the conventional Fraunhoffer pattern, confirming their uniformity. In the QH regime, when Landau quantization is fully developed, regions of superconductivity can be observed on top of the conventional QH fan diagram. The measured supercurrent is very small, on a few nA scale.

It is evident that the traditional Andreev bound states cannot exist in the quantum Hall regime, when the bulk of the junction is gapped by the Landau quantization so that a current may only flow along the edges. Indeed, one chiral edge state can only conduct charge carriers (both electrons and holes) in one direction. Therefore, both edges have to be involved to supercurrent between the two contacts. However, edge states with opposite momenta are separated by the width of the junction, which greatly exceeds the coherence length of the MoRe electrodes (a few nanometers). We discuss the mechanisms that couple the edge states on the opposite sides of the sample.




**Quantum Hall fan diagrams: the left panel is measured with 3nA DC current, which suppresses superconductivity revealing well-quantized plateaus. The right panel is measured with zero DC current and an AC excitation of only 50 pA; the dark spots of suppressed resistance on top of plateaus correspond to regions of superconductivity, which extend up to ~2 Tesla.**

References
[F. Amet, C.-T. Ke, I. V. Borzenets, J. Wang, K. Watanabe, T. Taniguchi, R. S. Deacon, M. Yamamoto, Y. Bomze, S. Tarucha and G. Finkelstein. Science (2016)]

# Minimal excitations in the fractional quantum Hall regime

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Abstract

We study the minimal excitations of fractional quantum Hall edges, extending the notion of levitons [1]-[2] to interacting systems. Using both perturbative and exact calculations, we show that they arise in response to a Lorentzian potential with quantized flux. They carry an integer charge, thus involving several Laughlin quasiparticles, and leave a Poissonian signature in a Hanbury-Brown and Twiss partition noise measurement at low transparency. This makes them readily accessible experimentally, ultimately offering the opportunity to study real-time transport of Abelian and non-Abelian excitations.

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# Unconventional transport and noise in the second Landau Level.

K. Bennaceur, C. Lupien, G. Gervais, B. Reulet, L.N. Pfeiffer and K.W. West

2D electron gas (2DEG) in magnetic with the interplay of electron interaction is an unmatched playground to observe a large variety of exotic electronic phases. The Fractional states of the quantum Hall effect usually appear at low filling factor, especially in the first (N=0) Landau level . At higher Landau level, where the ratio between the Coulomb energy and the cyclotron energy is larger, crystalline phases such as bubble or stripe phase have been observed.

The second Landau level (SLL) is particularly interesting as it hosts a tight competition between crystalline and fractional phases [1,2,3], as well as more exotic states such as the 5/2. This state in particular is believed to carry non abelian excitations and is far from being well understood.

We have measured bulk dc transport and low frequency current noise in the SLL of an ultra-high mobility GaAs/AlGaAs 2DEG. We have used a Corbino geometry [4] which allows to probe the longitudinal conductance $\sigma_{xx}$ without any edge state contribution. We have observed unconventional features both in the differential conductance and in the noise, which are suggesting a coexistence of fractional quantum Hall and crystalline phases.

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# New paradigm for edge reconstruction of hole-conjugate fractional states

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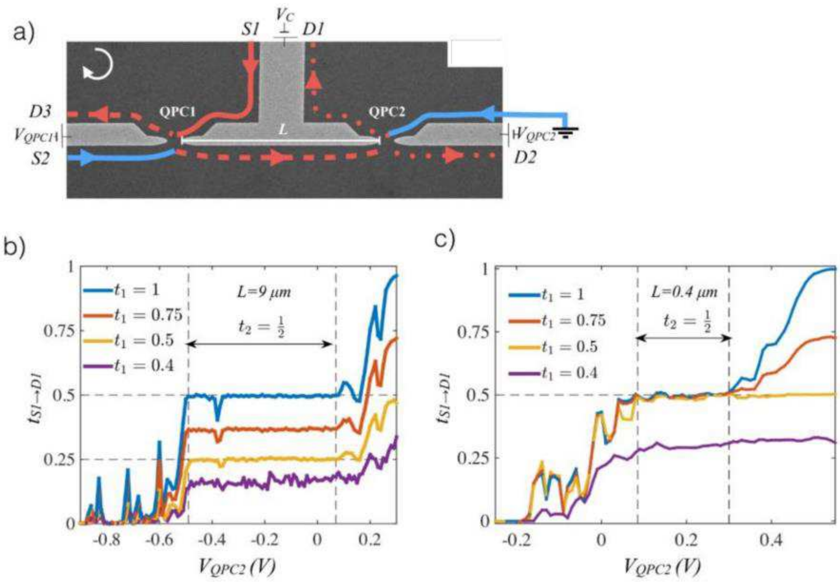
In this presentation we provide evidence of a new model for hole-conjugate fractional states $\upsilon$ = 2/3. While the present accepted model [1,2] postulates of a single ‘downstream’ charge channel with conductance 2/3 ⁄ $e$^2 /$h$ and an ‘upstream’ neutral channel, we show that the current is carried by two downstream edge modes, each with conductance 1/3 ⁄ $e$^2 /$h$. We find that if the two channels are driven out of equilibrium, inter-mode equilibration takes place; leading the two channels to behave as a single mode with conductance 2/3 ⁄ $e$^2 /$h$. This unexpected edge reconstruction suggests a non-trivial interplay between charge and neutral modes that could be a major decoherence source. We therefore have investigated the transmission of these neutral modes through a quantum point contact and show that the neutral mode signal is mainly attached to the inner edge channel, in agreement with the latest theoretical models developed [3].



a)Scanning electron microscope (SEM) image of the device. b) Transmission from S1 to D1 (t_(S1→D1)) as function of V_QPC2 for different t_1 for the L=9µm device. c) Same experiment with L=400 nm

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# Weak and strong non-linear effects in Josephson junction chains

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In the first part of my talk I will present our microwave transmission measurements on propagation modes in Josephson junction chains containing several hundreds of junctions. After some preliminary measurements [1] we have done a more systematic measurement in an improved measurement-set-up that I will present. Some of the chains have been imbedded into the microwave strip line, while others have been coupled capacitively to it. The latter configuration enables a study of the internal quality factor of the chain while the first one is more suited to study quantitatively the Kerr effects occurring between different modes in the chain. The experimental dispersion curve fits well the theoretical prediction. We measured the Self- and Cross Kerr effects by two-tone spectroscopy measurements. We deduce from our measurements the Self- and Cross Kerr coefficients for the first 8 modes and compare them to theory.
In the second part of my talk, I will show our recent results on the realization of a fluxonium qubit. I will discuss spectroscopy measurements and measurements of the relaxation and decoherence time of this qubit.

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# Antibunched photons emitted by voltage biased Josephson junction

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Microwave radiation is most simply generated by alternating currents driven through a classical conductor, but can also be emitted by dc biased quantum conductors. This stems from the quantum fluctuations of the current reflecting the probabilistic transfer of granular charges through the conductor. Can one take advantage of these peculiar properties of quantum electrical transport to produce radiative states with strong non-classical properties such as, e.g., single photons ? I will show that indeed the photons emitted by a dc biased junction coupled to a high impedance mode are strongly antibunched. This reflects the fact that in such a strange regime, the presence of a photon in the resonator inhibits the tunneling of a Cooper pair.

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# Squeezing by a quantum conductor

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Abstract (max 1/2 page including references+ 1 illustration if needed)

Hybrid architectures integrating mesoscopic conductors in microwave cavities have a great potential for investigating unexplored regimes of electron–photon coupling. In this context, producing nonclassical radiation, such as a squeezed vacuum state, is a key step towards quantum communication with scalable solid-state devices.
We show here that a tunnel junction is able to generate a squeezed steady state in a microwave cavity when excited parametrically by a classical AC voltage source. Photon-assisted tunneling of electrons is accompanied by the emission of pairs of photons in the cavity, thereby engineering a driven squeezed state. In contrast to parametric amplifiers, squeezing here is caused by dissipation in the electronic bath. For a tunnel junction, we show theoretically that squeezing can be optimized by a pulse shape consisting of a periodic series of delta peaks. Squeezing is generally enhanced by non-linearities. We also find perfect squeezing in the case of a tunnel junction affected by a strong dynamical Coulomb blockade environment.

References

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# What are the impedance combination rules in quantum circuits?

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Quantum Point Contacts (QPC) or connected molecules are paradigmatic quantum electronic component whose transport properties are often described in the Landauer-Büttiker (LB) scattering formalism. This notably yields their conductance through the celebrated “Landauer formula”.

When several such quantum components are assembled in a lumped-element circuit however, the “Landauer formula” breaks down: Quantum components interact with their surrounding in a nonlinear way that prevents using the usual impedance combinations rules to predict the behavior of the circuit. In the limit case of tunnel junctions, this interaction is quantitatively explained by the theory of Dynamical Coulomb Blockade.

Here will show that the LB formalism can be extended in order to take into account quantum voltage fluctuations, generalizing the Dynamical Coulomb Blockade theory to conductors of arbitrary transparency [1].

Using this approach we quantitatively account for the measured conductance of a QPC in series with large resistances [2, 3] for which there was previously no satisfactory theory.

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# Direct measurement of the electron energy relaxation dynamics in metallic wires [1].

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Energy relaxation of electrons in a conductor is a very important issue both on an applied and fundamental point of view. For example, the energy relaxation rate determines the bandwidth of hot electron bolometers used to detect electromagnetic radiation through heating of the electron gas [2]. On a fundamental point of view, inelastic times are key parameters for example for quantum correction to electron transport, electron localization at low temperature [3] and non-equilibrium effects [4].

I will present measurements of the dynamical response of thermal noise to an ac excitation in conductors at low temperature. From the frequency dependence of this response function - the (noise) thermal impedance - in the range 1 kHz-1 GHz we obtain direct determinations of the inelastic relaxation times relevant in metallic wires at low temperature: the electron-phonon scattering time and the diffusion time of electrons along the wires. Combining these results with that of resistivity provides a measurement of heat capacity of samples made of thin film. The simplicity and reliability of this technique makes it very promising for future applications in other systems.

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# Quantum transport in many-body localized systems

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Whether and how electron-electron interactions restore a finite conductivity in disordered systems undergoing Anderson localization is a longstanding problem in theoretical and experimental physics. Recent theoretical works argued that interactions in disordered systems drive a transition from a metallic phase to a completely new phase of matter called Many-Body Localization (MBL). In this phase, the system is supposed to be perfectly insulating for temperatures below a critical temperature Tc, to be unable to thermalize and to reliably store quantum information. In this talk, I will review recent theoretical and experimental progress concerning these systems and focus on their quantum transport properties. In particular, I will discuss the behavior of persistent currents in disordered one-dimensional rings hosting interacting electrons and show how persistent currents, in particular a strongly related quantity, Drude weights, give sensitive information about the MBL transition based on its transport properties.

# Title

Charge and spin diffusion on the metallic side of the metal-insulator transition: a self-consistent approach

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Abstract (max 1/2 page including references+ 1 illustration if needed)

We develop a self-consistent theory describing the spin and spatial electron diffusion in the impurity band of doped semiconductors under the effect of a weak spin-orbit coupling. The resulting low-temperature spin-relaxation time and diffusion coefficient are calculated within different schemes of the self-consistent framework. The simplest of these schemes qualitatively reproduces previous phenomenological developments, while more elaborate calculations provide corrections that approach the values obtained in numerical simulations. The results are universal for zinc-blende semiconductors with electron conductance in the impurity band, and thus they are able to account for the measured spin-relaxation times of materials with very different physical parameters. From a general point of view, our theory opens a new perspective for describing the hopping dynamics in random quantum networks [1].

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**Out-of-equilibrium Kondo transport**

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Since its birth on 1964, as an explanation of the low-temperature resistivity of impure metals, the Kondo model has fostered or accompanied a tremendous amount of original ideas in theoretical physics: non-perturbativeness, renormalization group, integrability… With the ability to manipulate electrons one by one, it was reborn in the 90's in the context of mesoscopic physics. This second life is still under development. After a brief survey of the Kondo effect at equilibrium, this talk will discuss the Kondo physics out-of-equilibrium, addressing the Kondo effect signature in the I-V characteristics, as well as in the (ac/dc) noise.

# Non-equilibrium Noise and Symmetry of the Kondo effect

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Most of the time, electronic excitations in mesoscopic conductors are well described, around equilibrium, by non-interacting Landau quasi-particles. This allows a good understanding of the transport properties in the linear regime. However, non-equilibrium properties beyond this regime have still to be established.

Kondo effect is a paradigm of such a many body state, which can be realized in a carbon nanotube (CNT) quantum dot. As CNT possess spin and orbital quantum numbers, it is possible to investigate the usual twofold degenerate SU(2) Kondo effect as well as the four fold degenerate SU(4) state by tuning the degeneracies and filling factor.

Combining transport and current noise measurements in such a dot, we have identified the SU(2) and SU(4) Kondo states [1]. We show that, a two-particle scattering process due to residual interaction emerges in the non-equilibrium regime. The effective charge e*, which characterize this peculiar scattering, is determined to be $e^*/e = 1.7 \pm 0.1$ for SU(2) and $e^*/e = 1.45 \pm 0.1$ for SU(4), in perfect agreement with theory [2].

This result demonstrates that current noise can detect unambiguously the many-particle scattering induced by the residual interaction and the symmetry of the ground state.

In addition, we manage to induce a continuous transition from SU(4) to SU(2) with the magnetic field, which allowed us to monitor the evolution of the fundamental properties (transmission channels and effective charge) along this quantum crossover.

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# Cavity quantum electrodynamics with carbon nanotubes : from atomic-like systems to condensed matter

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Cavity quantum electrodynamics techniques have turned out to be instrumental to probe or manipulate the electronic states of nanoscale circuits. Recently, cavity QED architectures have been extended to quantum dot circuits. These circuits are appealing since other degrees of freedom than the traditional ones (e.g. those of superconducting circuits) can be investigated. I will show how one can use carbon nanotube based quantum dots in that context. In particular, I will focus on how to engineer a strong electron-photon interaction by dressing an electronic transition with coherent injection of Cooper pairs.

Quantum dots also exhibit a wide variety of many body phenomena. The cQED architecture could also be instrumental for understanding them. One of the most paradigmatic phenomenon is the Kondo effect which is at the heart of many electron correlation effects. I will show that a cQED architecture has allowed us to observe the decoupling of spin and charge excitations in a Kondo system.

References

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# Measurements of transmission phase across a large quantum dot

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The phase of electron wave functionis at the heart of quantum interference phenomena in coherent electron transport such as universal conductance fluctuations or weak localization. It can be accessed by inserting a quantum dot into one arm of a two-path interferometer and for the case of the Coulomb blockade regime, a □-phase shift is acquired across each Coulomb peak. In addition, when scanning over several Coulomb peaks, unexpected abrupt phase jumpsbetween all successive Coulomb peaks have been observed [1, 2]. Despite important theoretical efforts [3-5], this phenomenon is yet to be explained and represents one of the longest standing puzzles in mesoscopic physics.
Here we report on transmission phase measurements of a quantum dot containing hundreds of electrons. We scan the transmission phase over a long sequence of Coulomb peaks and find that the transmission phase shows predominantlyphase lapsesbut also smooth phase evolution.Furthermore, we demonstrate that a modification of the quantum dot shapeallows us to alternate the occurrence of phase lapses. Our results give a new insight into the understanding of the transmission phase through a quantum dot.

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# Thermal decay of charge fluctuations in mesoscopic circuits

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We study transport properties and the charge quantization phenomenon in a small metallic island connected to two leads through two quantum point contacts[1,3]. The linear conductance is calculated perturbatively in tunneling coupling as a function of temperature $T$ and gate voltage $Q_0$ in cases of different transmission coefficients of contacts. Two regimes are considered: quantum, $T << E_C$ and thermal, $T >> E_C$ , where $E_C$ is the charging energy of the isolated island. As a function of gate voltage, the conductance shows Coulomb blockade oscillations. Our predictions of these oscillations in quantum regime coincide with previous results of A. Furusaki and K. A. Matveev[2]. In thermal regime the temperature dependence of linear conductance consists of product of power-law prefactor and exponential decay. The exponential temperature dependence is robust, while the power-law behavior depends on the geometry of circuit. Differential capacitance is calculated in single tunnel junction case. It is demonstrated that the pre-factor of correction to differential capacitance is given by linear function of temperature in contrast with conductance, while exponential decay does not change. Our results are confirmed by experimental data from group of F. Pierre[3].

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# A practical quantum realization of the ampere from the elementary charge

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The International System of units (SI) has always progressed following the scientific knowledge with the aim of being universal and of reducing the measurement uncertainties. In a very near future it is planned to base the SI on seven defining constants, among which are the Planck constant $h$ and the elementary charge $e$ [1-3]. This modernization will allow the SI conform realizations of the electrical units, the volt and the ohm, from the Josephson effect and the quantum Hall effect, with unprecedented low uncertainties only limited by their implementation. Another advantage is that the ampere, once defined from $e$, can be realized using quantum effects, either by using single electron tunneling devices or by applying directly Ohm's law to the quantum voltage and resistance standards.
In this context, we have developed an original implementation of Ohm's law applied to a special circuit combining a programmable Josephson voltage standard (PJVS), a quantum Hall resistance standard (QHRS) and a highly-accurate superconducting amplifier to realize a programmable quantum current generator (PQCG) [4]. We have demonstrated the accuracy of the generated current in the milliampere range to 1 part in $10^8$. This new quantum current standard can generate currents down to the microampere range with such accuracies and we have shown that it can be used to efficiently calibrate digital ammeters. It competes seriously with the electron pumps which have reached 2 parts in $10^7$ at 90 pA [5] only recently and at the expense of big research efforts over the last two decades. More fundamentally, the PQCG will become a direct realization of the future definition of the ampere from the elementary charge with an uncertainty at the level of 1 part in $10^8$ in the new SI.

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# Imaging magnetism at the nanoscale with a single spin microscope

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In the past years, it was realized that the experimental methods allowing for the detection of single spins in the solid-state, which were initially developed for quantum information science, open new avenues for high sensitivity magnetometry at the nanoscale. In that spirit, it was recently proposed to use the electronic spin of a single nitrogen-vacancy (NV) defect in diamond as an atomic-sized magnetic field sensor [1,2]. This approach promises significant advances in magnetic imaging since it provides non-invasive, quantitative and vectorial magnetic field measurements, with an unprecedented combination of spatial resolution and magnetic sensitivity under ambient conditions.

In this talk, I will show how scanning-NV magnetometry can be used as a powerful tool for fundamental studies in nanomagnetism, focusing on chiral domain walls and magnetic skyrmions in ultrathin ferromagnetic wires [3,4] and spin spirals in multiferroic materials.

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# Controlling spin relaxation with a cavity

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Spontaneous emission of radiation is one of the fundamental relaxation mechanisms for a quantum system. For spins, however, it is negligible compared to non-radiative relaxation-processes due to their weak coupling to the electromagnetic field. In 1946, Purcell realized [1] that spontaneous emission is strongly enhanced when the quantum system is placed in a resonant cavity - an effect now used to control the lifetime of systems with an electrical dipole [2]. Here, by coupling donor spins in silicon to a high quality factor superconducting microwave cavity of small mode volume, we reach the regime where spontaneous emission constitutes the dominant spin relaxation channel [3]. The relaxation rate is shown to depend on the cavity quality factor, on the spin-cavity coupling and on the spin-cavity frequency detuning, proving that the quantum fluctuations of the cavity field are indeed responsible for the spin relaxation. Moreover, the spin relaxation rate is increased by three orders of magnitude when the spins are tuned to the cavity resonance, showing it can be engineered and controlled on-demand. Our results provide a novel way to initialize any spin into its ground state, with applications in magnetic resonance and quantum information processing. They also show for the first time an alteration of spin dynamics by quantum fluctuations; as such they represent a step towards the coherent magnetic coupling of a spin to microwave photons.

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# Spin squeezing in ultracold atoms: Towards metrological applications

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Entanglement has grown from a quantum curiosity into a cornerstone of modern quantum theory, and acts as a resource in future quantum technologies such as quantum metrology. The spin-squeezed state is the prime example of a highly entangled many-particle state having the potential to improve metrological devices, such as atomic clocks and interferometers. Indeed, some of these devices have reached a level of performance where the dominant noise source is now the "projection noise" - the fact that each of the $N$ spin-1/2 atoms being probed can only give a "yes or no" result rather than a continuous value, introducing 1/sqrt(N) stastitical fluctuations. In spin-squeezed states, quantum correlation between the atoms reduces these fluctuations without impacting the mean value of the measurement.
Producing spin-squeezed states in the lab requires an interaction to create the entanglement. Two approaches exist in ultracold atoms. The first is to exploit collisional interactions [1]: if their strength depends on the internal state, a spin-squeezed state results after some interaction time. I will present an experiment [2] peformed in collaboration with the French time and frequency metrology laboratory SYRTE, using our Trapped-Atom Clock on a Chip (TACC) [3,4], where we have used this type of interaction in a Bose-Einstein condensate (BEC). We have been able to create a situation in which the spin squeezing occurs sponteneously, without requiring the state-dependent potentials or Feshbach resonances that were required in earlier experiments. This method could be used with minimum technical overhead in BEC-based atom interferometers, an emerging subject in atom interferometry research.
The principle of spin squeezing now being well established, an important outstanding goal is to take it to a metrologically relevant level, implementing it on an actual atomic clock. We are working towards this goal by adding cavity-based spin squeezing [5] to TACC, to reach the level of 10^-13 s^-1/2 fractional stability. This is made possible by employing the fiber Fabry-Perot microcavity technology developed in our group, which has already shown its potential to create multiparticle entanglement [6].

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## Quantum error correction with superconducting circuits

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The field of quantum information processing (quantum computing and quantum communication) has seen a tremendous progress during the past few decades. Many proof-of-principle experiments on small-scale (few physical degrees of freedom) quantum systems have been realized within various physical frameworks such as NMR (Nuclear Magnetic Resonance), trapped ions, cavity quantum electrodynamics, linear optics and superconducting circuits. Despite all these achievements, and in order to make this a useful technology, a major scaling step is required towards many-qubit (quantum bit) protocols. The main obstacle here is the destruction of quantum coherence (called decoherence) due to the interaction of the quantum system with its environment. The next critical stage in the development of quantum information processing is most certainly the active quantum error correction (QEC). Through this stage, one designs, possibly using many physical qubits, an encoded logical qubit which is protected against major decoherence channels and hence admits a significantly longer effective coherence time than a physical qubit. While a theory of quantum error correction has existed and developed since mid 1990s, the first experiments are being currently investigated in the physics labs around the world. After reviewing some of the theory behind this field, as well as some recent experimental results, I will present our approach to this subject. In particular, I will overview a series of recent theoretical proposals, and preliminary experimental developments, to enable a hardware-efficient paradigm for quantum error correction. These proposals are based on two main ingredients: 1- encoding of information in the so-called Schrödinger cat states of microwave radiation in a superconducting resonator, 2- application of parametric pumping methods to stabilize a manifold of quantum states. I will also present some new proposals to push these methods towards fault-tolerant quantum information processing protocols. One central requirement concerns the development of degeneracy-preserving quantum non-demolition photon-number parity measurements. We propose to achieve such measurements by exploring a new regime of non-linear interactions provided by high-impedance Josephson circuits.

This is a joint work with many collaborators from Inria and Yale university. The experimental work has been performed at Yale by the groups of Michel H. Devoret and Robert J. Schoelkopf.

# Using Spontaneous Emission of a Qubit as a Resource for Feedback Control

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When the relaxation of a qubit comes from its coupling to a photonic channel, each relaxation event is associated with the release of a photon. By counting the photons emitted by fluorescence, discrete quantum jumps of the qubit can be observed. The discreteness of the quantum jumps is in fact related to the nature of the light detector. We have instead used a superconducting parametric amplifier, which performs a heterodyne measurement of the fluorescence field emitted by a superconducting qubit [1]. We show that in that case, the evolution of the qubit state for a particular outcome of the detector is continuous and stochastic. In some cases, the excitation probability of the qubit can even increase temporarily despite the fact that the corresponding information is encoded in the light emitted during relaxation. The predictive power of such *quantum trajectories* is validated through independent tomographic reconstruction. We then use the information retrieved from the fluorescence field in a feedback loop to perform persistent control of the qubit [2]. A simple analog treatment of the detected signal, fed back to the system through microwave drives, allows to stabilize permanently any targeted state of the qubit.

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# Near quantum-limited amplification and conversion based on a voltage-biased Josephson junction

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Josephson parametric amplifiers[2], have proven to be an indispensable tool for a wide range of experiments on quantum devices in the microwave frequency regime, because they provide the lowest possible noise[1]. However, parametric amplifiers remain much more difficult to use and optimize than conventional microwave amplifiers.

Recent experiments with superconducting circuits consisting of a DC voltage-biased Josephson junction in series with a resonator have shown that a tunneling Cooper pair can emit one or several photons with a total energy of $2e$ times the applied voltage[3]. We present microwave reflection measurements on the device in [3], indicating that amplification is possible with a simple DC voltage-biased Josephson junction. We also show that this amplification adds noise close to the limit set by quantum mechanics for phase preserving amplifiers[1]. For low Josephson energy, transmission and noise emission can be explained within the framework of $P(E)$ theory of inelastic Cooper pair tunneling and are related to the fluctuation dissipation theorem (FDT). We also experimentally demonstrate, by controlling the applied DC voltage, that our device can act as both an amplifier and a frequency converter.

Combined with a theoretical model, our results indicate that voltage-biased Josephson junctions might be useful for amplification near the quantum limit, being powered by simple DC voltage and providing a different trade-off between gain, bandwidth and dynamic range, which could be advantageous in some situations[4].

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# Microwave photon router controlled by the quantum phase of a superconducting qubit

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In the last decade, superconducting circuits have proven to be one of the most controlled and advanced physical systems to process quantum information. With an unprecedentedly large coupling to electromagnetic modes, they can explore with ease the field of cavity quantum electrodynamics and all its applications. In particular, they enable a fine quantum control of microwave modes, allow to realize quantum feedback experiments and show outstanding preliminary results on quantum computing and quantum simulations. In the usual configuration of these so-called circuit-QED experiments, a superconducting qubit is non-resonantly coupled to a microwave cavity so that the qubit can realize a quantum non-demolition measurement of the state of the microwave mode, and reciprocally. Interestingly, in almost all experiments so far, the microwave fields at the qubit transition frequency could always be treated as classical input fields driving the qubit, without considering or measuring the corresponding output fields. This is in stark contrast with many physical systems (cold atoms, NV centers, photonic waveguides…) that couple to visible light and for which resonance fluorescence is a tool of choice for detection.

Until recently, fluorescence of superconducting qubits was indeed only demonstrated to contain a footprint of the qubit state. Here we investigate the interplay of different microwave modes controlled by the phase of a resonant superconducting qubit. We first demonstrate that one can single out the spontaneous and stimulated photons emitted by a qubit thanks to a nearly-quantum-limited phase preserving amplifier. Then we consider an experiment where two transmission lines are used to drive a qubit with the same Rabi frequency $\Omega$ but opposite phase. Despite the fact that interferences exactly cancel the impact of both lines on the qubit dynamics, we predict and demonstrate that a transfer of energy occurs from one line to the other, proportionally to the coherence $\Omega\langle\sigma_x\rangle$, as expected from resonance fluorescence. This experiment then realizes the first energy router whose direction is given by the phase of a quantum superposition.

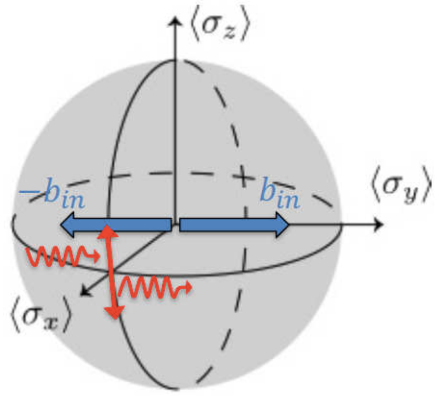


Figure 1: Coherent energy transfer across two microwave modes

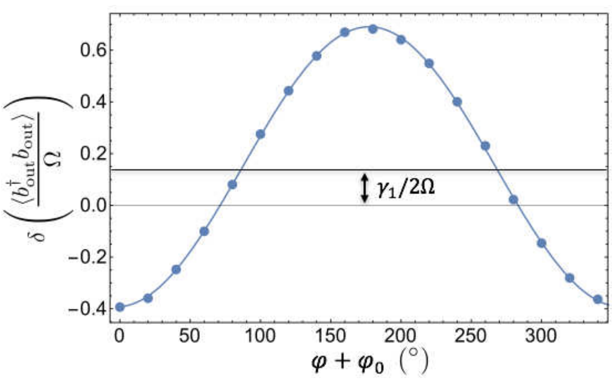


Figure 2 : Dependence of the photon flux on the qubit's quantum phase

# Optical Manipulation of Single Flux Quanta

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The semiconductor electronics scaling road map will probably reach its physical fundamental limits within the next decade. Alternative technologies such as superconducting electronics are appealing due to higher operating frequencies together with fundamentally lower switching energies. In this context, a promising method requires the manipulation of individual flux quanta close to a Josephson junction, the "elementary brick" of superconducting circuits. Yet, handling of individual vortices remains challenging and has been performed only with local probe scanning microscopies, slow techniques that are heavy to implement especially in a cryogenic environment. New approaches consisting in all-optical fast operation of Josephson junctions would be particularly promising.

In this work[1], we introduce for the first time the concept of laser manipulation of individual flux quanta. We developed a simple far-field optical method based on local heating of the superconductor with a focused laser beam to realize a fast, precise and non-invasive manipulation of an Abrikosov vortex, in the same way as with optical tweezers. We showed that our technique provides a perfect basis for sculpting the magnetic flux profile in superconducting devices like a vortex lens or a vortex cleaner. By choosing the appropriate laser parameters, we realized various regimes of vortex manipulation, from the precise and rapid positioning of individual vortices to the generation of tight vortex bunches.

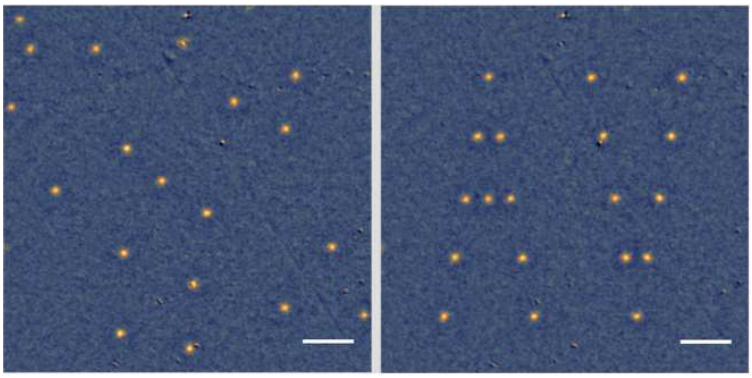

*Fig Left image: spontaneous vortex distribution in a 90 nm-thick niobium film after field-cooling. Right image: same region after single vortex optical repositioning into an artificial pattern forming the letters A V for "Abrikosov Vortices". The scale bar is 20 µm.*

*1- "Optical manipulation of single flux quanta" I. S. Veshchunov et al. Nature Communications 7 (2016) 12801 (2016)*

# Hyperbolic cooling of graphene Zener-Klein transistors

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Abstract: Engineering of cooling mechanisms is a bottleneck in nanoelectroniscs. In graphene/hBN transistors, Wiedemann-Frantz cooling[1] and supercollision-cooling[2] prevails, and the latter is suppressed in high mobility graphene/hBN samples and substituted by the super-Planckian radiation[3]of hyperbolic phonon-polaritons (HPPs) in the hBN substrate. Using electrical Joule heating and sensitive noise thermometry in several GHz range we report on prevailing HPP cooling in the upper Reststrahlen-band of hBN at high bias. We predict and observe its activation threshold, along with interband Zener-Klein tunneling. HPP cooling is able to evacuate at least several GW/m2 to the bottom gate, resulting in an unusual clipping of electronic temperature. As a scattering counterpart, HPPs of the lower Reststrahlen-band control current saturation at high doping. The combination of both mechanisms promotes graphene/hBN as a valuable nanotechnology for applications in the high power devices and radio frequency electronics.

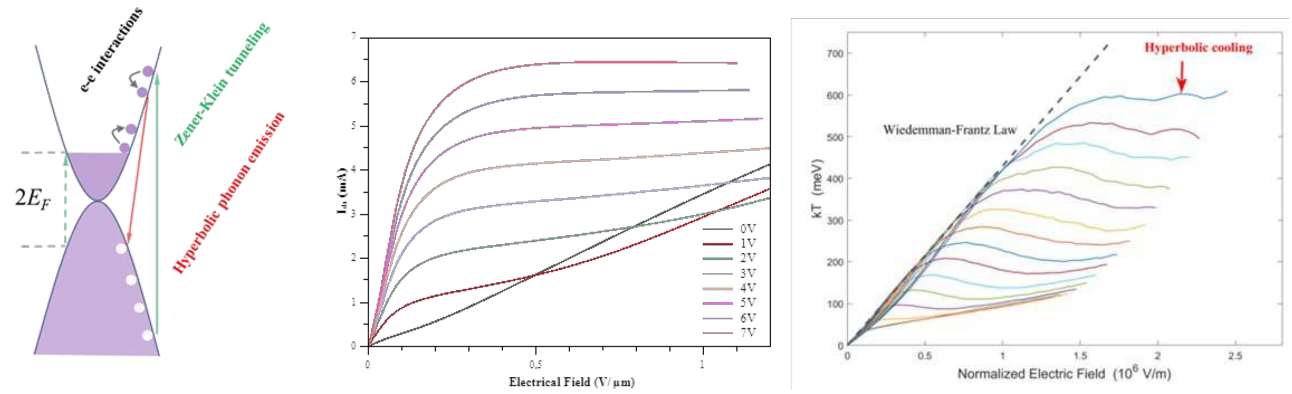


Figure- Schematic of energy relaxation, Current saturation, and Noise electron temperature.

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***On demand angle control in van der Waals heterostructures***

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Van der Waals (vdW) heterostructures are formed by intercalation of layered, few atoms thick crystalline materials with different electronic, mechanical and optical properties (e.g. semiconductors, insulators). Beyond the individual study of such two-dimensional materials in the ultra-clean limit, this allows us to mix the properties of several materials, yielding new and as of yet inaccessible physics. While these heterostructures have become the gold standard for probing the electronic and optical properties of graphene and other exotic materials, the control over a crucial degree of freedom has been lacking so far: the relative angle between layers, or layers alignment. This angle changes the heterostructures' properties in dramatic ways. A well-known example is graphene on boron nitride, where the relative angle between the two materials generates a periodic (Moiré) potential in graphene, strongly modifying its band structure. The absence of precise control over this angle has left these new properties out of reach so far. Here we developed an approach consisting in realizing heterostructures where the crystallographic alignment between layers can be manipulated in situ using an atomic force microscope to rotate one layer, while its mechanical and electronic properties are measured. We present results of in situ manipulation of a Moiré potential as well as tuning of the transmission between graphene layers by changing the relative orientation of the graphene crystals, Figure 1 a and b. In the later we found a 60° periodicity corresponding to crystal symmetry with additional sharp decreases around 22° and 39° (Fig. 1-c), which are among the commensurate angles of twisted bilayer graphene [1].

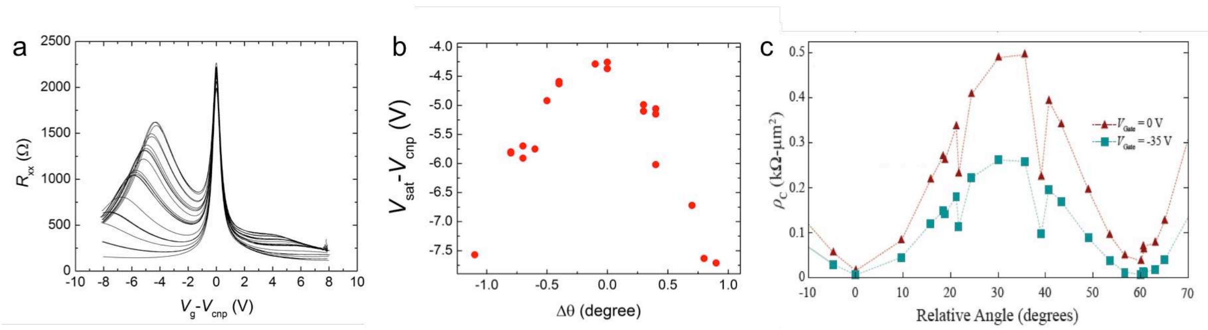


**Figure 1. Angle control in van der Waals heterostructures**. **a** Resistance as a function of the gate voltage for different angle alignments in a graphene/h-BN structure. **b** Position of the satellite peak as a function of the angle. **c** Resistivity across two graphene layers as a function of the angle.

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# Photon-Assisted Shot Noise in Graphene in the Terahertz Range

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When subjected to electromagnetic radiation, the fluctuation of the electronic current across a quantum conductor increases. This additional noise, called photon-assisted shot noise, arises from the generation and subsequent partition of electron-hole pairs in the conductor. The physics of photon-assisted shot noise has been thoroughly investigated at microwave frequencies up to 20 GHz, and its robustness suggests that it could be extended to the terahertz (THz) range. Here, we present measurements of the quantum shot noise generated in a graphene nanoribbon subjected to a THz radiation. Our results show signatures of photon-assisted shot noise, further demonstrating that hallmark time-dependent quantum transport phenomena can be transposed to the THz range.

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F.D. Parmentier, L.N. Serkovic-Loli, P. Roulleau, D.C. Glattli, Phys. Rev. Lett. **416,** 227401 (2016).

# Graphene response to charge disorder on the local scale

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The charge carrier density in graphene on a dielectric substrate such as $SiO_2$ displays inhomogeneities, the so-called charge puddles. Because of the linear dispersion relation in monolayer graphene, the puddles are predicted to grow near charge neutrality, a markedly distinct property from conventional two-dimensional electron gases [1]. We combine *in situ* scanning tunneling microscopy/spectroscopy, Kelvin probe force microscopy and transport measurements on a single mesoscopic graphene device. This allows us to directly observe the puddles' growth, both in spatial extent and in amplitude, as the Fermi level approaches the Dirac point [2]. Self-consistent screening theory provides a unified description of both the macroscopic transport properties and the microscopically observed charge disorder. We further show that local variations of the Fermi level with respect to the band structure are in one-to-one correspondence with changes in the local work function, down to the nanometer scale [3].

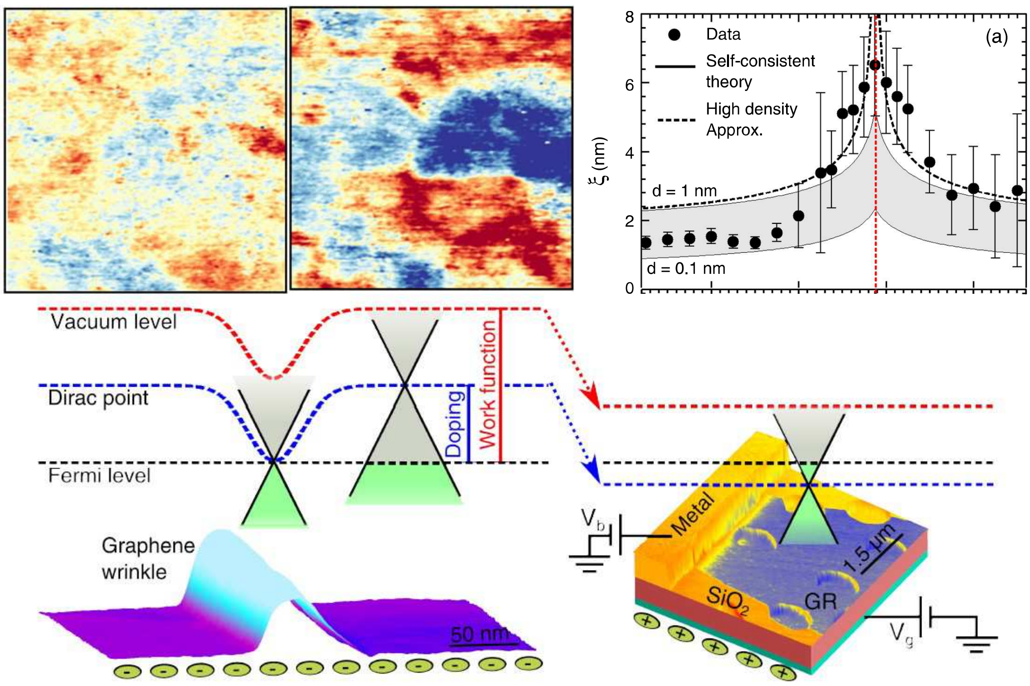


**Figure: Top row**: when the Fermi level is tuned from p-doping (left) to the Dirac point (center), doping inhomogeneities in single layer graphene grow, both in lateral extent and in amplitude. Right: puddles size dependence on back-gate voltage. **Bottom row:** as the Fermi level varies, either because of topographic features or back gate control, the graphene work function varies accordingly.

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# Imaging the Berry Phase from Friedel Oscillations in 2D Semimetals

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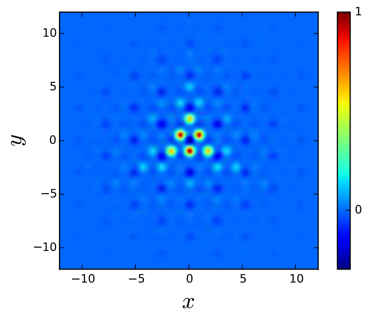

Electronic density around a localized impurity at the surface of ABC trilayer graphene. This interference pattern reveals the topological Berry phase that characterizes the semimetallic band structure.

The low-energy physics of rhombohedral N-layer graphene defines a two-band semimetal. Based on a generic low-energy description of 2D semimetals, we address the problem of elastic scattering through a realistic localized impurity located either on the surface of the material or within the bulk [1]. The analysis of the quantum interferences shows that the impurity induces Friedel oscillations in the electronic density on the two external layers. On the one hand, it tells us that monolayer graphene is the only material of the rhombohedral class that exhibits $1/r^2$-decaying Friedel oscillations, $r$ being the distance to the impurity. On the other hand, it turns out that the Fourier transform of the interference pattern also reveals the full low-energy band structure of the material, including the topological $\boldsymbol{\pi}$-quantized Berry phases that characterize the existence of nodal points in the spectrum. This means that, experimentally, these topological features may be imaged by scanning tunneling microscopy.

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