Quantum Mesoscopic Physics

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Abstract Booklet Talks

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Imaging the local band topology, orbital magnetism, and Chern mosaic in magic-angle graphene

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Topology is a key element governing the electronic and magnetic properties of 2D moiré materials. The topological electronic bands are classified by their Chern number C, which is considered to be a global topological invariant. The Chern number is governed by the Berry curvature that leads to orbital magnetization. Utilizing a scanning superconducting quantum interference device on a tip (SQUID-on-tip), we image the Berry-curvature-induced equilibrium orbital magnetization in magic-angle graphene, thus providing new means to resolve the local band topology on the nanoscale [1]. At integer filling ν=1, we observe a zero-field Chern insulator, which rather than being described by a global topologically invariant C, forms a Chern mosaic of microscopic patches of C= -1, 0, or 1, the boundaries of which carry chiral edge states. Upon further filling, we find a first-order phase transition due to recondensation of electrons from valley K to K', leading to irreversible flips of the local Chern number and orbital magnetization, and to the formation of valley domain walls giving rise to hysteretic anomalous Hall resistance. The findings shed new light on the structure and dynamics of topological phases in moiré devices.

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Tunable broken-symmetry orders and quantum Hall edge channels in graphene

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The zeroth Landau level of graphene under a magnetic field is a particularly interesting strongly interacting flat band because interelectron interactions are predicted to induce a rich variety of broken-symmetry states with distinct topological and lattice-scale orders. Evidence for these states comes mainly from indirect transport experiments that suggest that broken-symmetry states are tunable by boosting the Zeeman energy or by dielectric screening of the Coulomb interaction. In this talk, I will describe three distinct broken-symmetry phases in graphene that we have identified in transport and imaged using scanning tunneling spectroscopy. I will then discuss the real-space structure of quantum Hall edge states that we found to be free of electrostatic reconstruction.

Flat Bands and Quantum Geometry in Flatlands

Jeanie Lau
The Ohio State University

In a flat band, the electronic interactions dominate, leading to emergent correlated phases such as superconductivity and charge density waves. The advent of flatlands, i.e. two-dimensional (2D) materials provide us with unprecedented opportunities to design and engineer flat bands via stacking, magnetic fields, and twisting. For flat bands in flatlands, quantum geometric contributions become important. To illustrate this, I will focus on superconductivity in twisted bilayer graphene, in which the slow Fermi velocity and the small charge density appear to invalidate conventional BCS equations and present a paradox. The paradox is resolved by our experimental demonstration that the superfluid stiffness is dominated by the quantum geometric contribution. We also find that the band velocity in this Dirac superconductor constitutes a new limiting mechanism for the critical current, analogous to a relativistic superfluid. Finally, I will also present on flat bands in suspended few-layer graphene, where gate tunable magnetism is observed.

Single-shot Pauli spin and valley blockade readout in bilayer graphene quantum dots

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The Pauli blockade effect in coupled double quantum dots, forbidding transitions between states with mis-matching spin (or valley) quantum numbers, is not only a direct manifestation of the Pauli exclusion principle, but also a key feature for qubit manipulation and read-out. In bilayer graphene quantum dots, apart from spins up and down, the additional valley degree of freedom K- and K+ gives rise to an unconventional single-dot two-carrier ground state: spin-triplet valley-singlet, altering the canonical even-odd double dot Pauli spin blockade picture. This ground state can be switched to a spin-singlet valley-triplet by a perpendicular magnetic field, allowing us to switch between valley-blockade at low, and spin-blockade at higher magnetic field, for the two-carrier Pauli blockade (1,1) to (0,2) [1]. We demonstrate single-shot read-out with spin- and valley- Pauli blockade [2] in gate-defined bilayer graphene double quantum dots, and thereby the measurement of spin and valley characteristic relaxation times T1 between spin- or valley-triplet and singlet states. The spin-T1 is measured to be up to 60 ms at B = 700 mT corroborating recent demonstrations of single-dot Elzerman read-out [3]. By increasing the inter-dot tunnel coupling the spin-T1 is drastically reduced. Moreover, we observe outstandingly long valley-T1, longer than 500 ms at B = 250 mT and unlike spin, is robust with inter-dot tunnel coupling strength. This valley lifetime is comparable with the state-of-the-art spin- singlet-triplet T1 measured in Si/SiGe and Si/SiO2 and an order of magnitude longer than their T1 reported at such low magnetic field [4,5]. Our results pave the way for future demonstration of coherent valley-qubit oscillations, and thereby the development of qubits based on a material that is only two atomic layers thick. Combining our results with the electrical tunability of the valley g-factor demonstrated recently [6], new schemes of electrical qubit control become accessible.

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Singular orbital diamagnetism and paramagnetism in graphene

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Graphene is one the most studied materials in condensed matter because of its astonishing properties related to its linear dispersion relation. One of these properties is the diamagnetic divergent orbital susceptibility at the Dirac point. This characteristic, which is a striking signature of the anomalous π Berry phase in graphene, was predicted many decades before, but it has been challenging to measure at a single-flake level. Another exciting prediction concerns the orbital magnetism of 2D crystals in general. The existence of a divergent orbital paramagnetic susceptibility has been predicted. These singularities are expected at the saddle points of the band structure.

To realize our experiments he have used a new technique that involves highly sensitive giant magneto-resistant (GMR) probes in combination with chemical potential control through a gate modulation. By the means of this technique, we have measured the singular orbital diamagnetic susceptibility in monolayer graphene, for the first time at single-flake level. We have also measured the singular orbital paramagnetic susceptibility in graphene in a moiré superpotential that comes from the alignment of graphene and boron nitride. We also present the preliminary results of the orbital susceptibility of AB bilayer graphene, and its evolution when a perpendicular electric field is applied.

Our results open a new way to explore the orbital magnetism and currents in 2D materials. This experiment should also complement the investigation of the particularities of the geometry of the band structure of 2D crystals, particularly Berry phase anomalies or saddle points, or reveal the existence of ballistic loop currents along the edges of 2D topological insulators.

Tuning van der Waals heterostructures by pressure

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In van der Waals heterostructures the layer distance strongly affects the interaction between the layers. Therefore, pressure is an ideal tool to engineer the band structure of van der Waal materials [1]. Here we will show examples for the versatility of this method. First, I will show, how this allows the tuneability of the band structure of multi-layer graphene. Moreover, in WSe2/Gr structures spin-orbit coupling can be induced in graphene using proximity effects, which can be boosted using hydrostatic pressure [2]. The enhancement is confirmed using weak anti- localization measurements. Finally, I will also demonstrate the band structure tuning of magic-angle twisted double bilayer graphene [3]. We have performed thermal activation and magneto-transport measurements to reveal changes in the bandgaps of the system. We have observed a strong tuneability with pressure, which is confirmed by our theoretical calculations. Finally, we have also observed changes in the strength of electron-electron interactions and in the topological phases at the charge neutrality point in magnetic fields.

Heat equilibration of integer and fractional quantum Hall edge modes in graphene

François Parmentier
CNRS - SPEC

The fractional quantum Hall effect is one of the most intriguing phenomena of condensed matter physics, where electronic interactions in a two-dimension electron gas subjected to a strong magnetic field lead to the emergence of highly exotic states with highly unusual properties. Among these, the existence of neutral edge modes, carrying only energy along the edges of the sample in a direction upstream to that of charge transport, has driven more than three decades of research. Their charge neutral nature has made them singularly challenging to probe, such that they were only first observed in 2010. Since then, many works have addressed the thermal transport properties of neutral modes, in particular whether they exchange energy with their neighboring counterpropagating charged edge modes. Significant progress was recently made on this topic, but an important question remained unanswered: can upstream neutral modes exchange energy and thermalize with integer¬-charged edge modes located up to several hundreds of nanometers away from them? This question is far from trivial, as it can profoundly change our understanding of the quantum Hall effect in terms of independent transport channels, and affect the realization of future experiments seeking to explore and exploit the remarkable properties of fractional quantum Hall states. We present heat transport measurements in quantum Hall states of graphene demonstrating that the integer channels can strongly equilibrate with the fractional ones, leading to markedly different regimes of quantized heat transport that depend on edge electrostatics. Our results allow for a better comprehension of the complex edge physics in the fractional quantum Hall regime. G. Le Breton, R. Delagrange, Y. Hong, M. Garg, K. Watanabe, T. Taniguchi, R. Ribeiro-Palau, P. Roulleau, P. Roche, and F. D. Parmentier, Phys. Rev. Lett. 129, 116803 (2022).

Heat equilibration of integer and fractional quantum Hall edge modes in graphene

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From topology to quantum chaos in cavity-qubit coupled systems

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We consider a simple setup of two slow quantum harmonic oscillators strongly coupled to a qubit.
We show that any initial state decomposes into a pair of adiabatic components. This allows us to group the states of this system in two distinct dynamical classes. In the topologically non-trivial phase, each of these adiabatic components effectively pumps energy between the two oscillators, but in two opposite directions.

This separation of energy content of the oscillators thereby realizes a new kind of cat state [1].

At intermediate timescales, the adiabatic components are subjected to Landau-Zener transitions, which reverse the sign of the energy flow between the two oscillators. These non-adiabatic effects lead to a chaotic dynamics at longer times.

We show that these two distinct types of dynamical behaviors give rise to two distinct families of eigenstates lying at the same energy scales. One family is chaotic, associated to a non-trivial topology of the adiabatic dynamics, while the other one is not chaotic, associated to a trivial topology.

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Analog quantum control of magnonic cat states on-a-chip by a superconducting qubit

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We propose to directly and quantum-coherently couple a superconducting transmon qubit to magnons — the quanta of the collective spin excitations, in a nearby magnetic particle. The magnet's stray field couples to the qubit via a superconducting interference device (SQUID) leading to strong and tunable interactions. More specifically, we predict a resonant magnon-qubit exchange coupling, similar to the one studied in 3D cavity setups [1], and a novel magnon-qubit nonlinear interaction that is similar to the radiation-pressure coupling in optomechanics [2]. We show that the latter can be resonantly enhanced by dynamically driving the flux in the SQUID, and demonstrate a quantum control scheme to generate magnon-qubit entanglement and magnonic Schrödinger cat states with high fidelity. Our results [3] enrich the quantum control toolbox in magnonic devices and open new possibilities for constructing quantum magnonic networks on a chip.

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Passive two-photon dissipation for bit-flip error correction of a cat code

Antoine Marquet
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Bosonic codes offer a resource-efficient method to quantum error correction [1]. Of particular interest, autonomous correction was successfully demonstrated for cat codes [2–5], where the logical $|0\rangle$ and $|1\rangle$ states are coherent states of opposite amplitudes $|\alpha\rangle$ and $|-\alpha\rangle$ in a superconducting resonator with single-photon loss rates κ1 as low as possible. They correct bit-flip errors by either using the non-linearity of the oscillator or parametrically pumping couplers to produce two-photon dissipation at a rate κ2. The bit-flip time increases exponentially with |α|2 while the phase-flip rate only increases linearly with |α|2. In this work, we introduce and experimentally demonstrate a new superconducting circuit designed to correct for bit-flip errors of cat codes. Crucially, the two-photon dissipation does not require any pump, so that a single drive is required to stabilize the qubit manifold. This is obtained by nonlinearly coupling the cat qubit to a buffer mode that resonates at twice the frequency of the cat qubit. We experimentally demonstrate unprecedented ratios κ2/κ1, so that bit flip times well over a ms can be reached with a few photons only. We also demonstrate quantum gates on this corrected cat qubit. This work was partly supported by the grant ANR-19-QUAN-0006.

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Signatures of classical chaos in driven transmons

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Transmons are ubiquitously used in superconducting quantum information processing architectures. Strong drives are required to realize fast high-fidelity gates and measurements, including parametrically activated processes. We show that even off-resonant drives, in regimes routinely used in experiments, can cause strong modifications to the structure of the transmon spectrum rendering a large part of it chaotic. Chaotic states, often neglected through the hypothesis that the anharmonicity is weak, strongly impact the lifetime of the computational states. In particular, chaos-assisted quantum phase slips greatly enhance band dispersions. In the presence of a readout resonator, the onset of chaos correlates with high transmon-resonator entanglement, and an average resonator response centered on the bare resonator frequency. We define a photon number threshold to characterize the appearance of chaos-induced quantum demolition effects during strong-drive operations, such as dispersive qubit readout. More generally, chaos-induced phenomena such as the ones studied here are expected to be present in all circuits based on low-impedance Josephson junctions.

Joachim Cohen, AP, Ross Shillito, and Alexandre Blais, arXiv:2207.09361

Cloaking a qubit in a cavity

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Cavity quantum electrodynamics (QED) uses a cavity to engineer the mode structure of the vacuum electromagnetic field such as to enhance the interaction between light and matter. Exploiting these ideas in solid-state systems has led to circuit QED which has emerged as a tool to explore the rich physics of quantum optics and as a platform for quantum computation. In this talk, we introduce a simple approach to further engineer the light-matter interaction in a driven cavity by controllably decoupling a qubit from the cavity's photon population, effectively cloaking the qubit from the cavity. This is realized by driving the qubit with an external tone tailored to destructively interfere with the cavity field, leaving the qubit to interact with a cavity which appears to be in the vacuum state. We will introduce the theory of qubit cloaking and show how it can be exploited to cancel ac-Stark shift and measurement-induced dephasing, and to accelerate qubit readout. Experimental results obtained at ENS Lyon demonstrating these concepts will also be discussed.

Observation of Josephson Harmonics in Tunnel Junctions

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An accurate understanding of the Josephson effect is the keystone of quantum information processing with superconducting hardware. Here we show that the celebrated sin(φ) current-phase relation (CφR) of Josephson junctions (JJs) fails to fully describe the energy spectra of transmon artificial atoms across various samples and laboratories. While the microscopic theory of JJs contains higher harmonics in the CφR, these have generally been assumed to give insignificant corrections for tunnel JJs, due to the low transparency of the conduction channels. However, this assumption might not be justified given the disordered nature of the commonly used AlOx tunnel barriers. Indeed, by including higher Josephson harmonics in the transmon Hamiltonian, we obtain orders of magnitude better agreement between the computed and measured energy spectra. The measurement of Josephson harmonics in the CφR of standard tunnel junctions prompts a reevaluation of current models for superconducting hardware and it offers a highly sensitive probe for material scientists to optimize tunnel barrier uniformity.

Revealing the finite-frequency response of a bosonic quantum impurity

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Condensed matter systems are famously difficult to simulate on classical computers, due to the interplay between the exponentially large Hilbert space and interactions. As such, answering condensed matter physicists' interrogations - finding excitation spectra, phase transitions, etc. - would be a crucial demonstration of supremacy for quantum simulators. Circuit quantum electrodynamics has been put forward as an excellent experimental platform for such an analog simulator, thanks to its scalability, strong interactions, and fine experimental control. In this work (ArXiv:2208.03053v3), we propose an implementation of the boundary Sine-Gordon model. This bosonic impurity model has been thouroughly studied in the contexts of quantum dissipation as well as the bosonisation of 1D interacting fermionic matter. The high impedance superconducting circuit allows to enhance the quantum fluctuations beyond quadratic approximation regime to approach the model phase transition, while hallmarks of many-body behavior can be retrieved by simple spectroscopic method. A careful analysis of the reactive and dissipative part of the circuit response is provided, thanks to a microscopic model of the system. The many-body contribution to the response is computed via diagrammatic self-consistent method at finite temperature. It especially demonstrates how strong, broadband dissipation emerges from well separated degrees of freedom interacting through a Josephson term. Our microscopically calibrated model allows us to assess the current hardware limitations still forbidding access to the universal regime. Still, some experimental results already probe a strong coupling regime where perturbative approach breaks down, calling for more advanced theoretical tools to model many-body circuit QED.

Unimon qubit

Mikko Möttönen
Aalto University and VTT

Superconducting qubits seem promising for useful quantum computers, but the currently wide-spread qubit designs and techniques do not yet provide high enough performance. Here, we introduce a superconducting-qubit type, the unimon, which combines the desired properties of increased anharmonicity, full insensitivity to dc charge noise, reduced sensitivity to flux noise, and a simple structure consisting only of a single Josephson junction in a resonator. In agreement with our quantum models, we measure the qubit frequency, $\omega/(2\pi)$, and increased anharmonicity $\alpha/(2\pi)$ at the optimal operation point, yielding, for example, 99.9% and 99.8% fidelity for 13 ns single-qubit gates on two qubits with $(\omega, \alpha) = (4.49\,\text{GHz}, 434\,\text{MHz}) \times 2\pi$ and $(3.55\,\text{GHz}, 744\,\text{MHz}) \times 2\pi$, respectively. The energy relaxation seems to be dominated by dielectric losses. Thus, improvements of the design, materials, and gate time may promote the unimon to break the 99.99% fidelity target for efficient quantum error correction and possible useful quantum advantage with noisy systems.

Bibliography reference: [E. Hyyppä et al., Nature Communications 13, 6895 (2022)]

Magnetic field dependence of the quasiparticle parity lifetime in 3D transmons with thin-film Al-AlOx-Al Josephson junctions

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With quasiparticle losses becoming a major source of decoherence in superconducting qubits an improved understanding of the underlying mechanisms is paramount. Moreover, the magnetic field dependence of the quasiparticle parity lifetime is of interest for future topological qubits, which rely on combining superconductors with magnetic fields. Placing a thin-film aluminum transmon in a 3D copper cavity, we can measure its quasiparticle parity lifetime over a large range of magnetic fields, with in-plane fields up to 400 mT. While the charging energy EC remains unaffected, the magnetic field reduces the Josephson energy EJ by suppressing the gap as well as by Fraunhofer interference. Both effects modulate also the parity lifetime. Notably, we observe a marked increase of the parity lifetime over 150 mT, before it starts to decrease with higher fields. We discuss the possible roles of excess quasiparticles and photon-assisted transitions in determining the parity lifetime. The transmon parity is read out with a Ramsey- or Rabi-like sequence followed by single-shot readout; for small magnetic fields and high EJ/EC ratios, we use the more offset-charge-sensitive 1-2 transition.

Mesoscopic physics challenges (in) superconducting quantum devices

Ioan Pop
KIT

I will discuss three mesoscopic physics phenomena which significantly complicate the task of engineering coherent superconducting hardware: ionizing radiation interactions with the device substrate, long lived two level systems which imprint a memory in the qubit's environment, and fluctuations in the transparency of aluminum oxide tunnel barriers.

Gate-Accessible Superconductivity and Helical Modes in Monolayer WTe2

Valla Fatemi
Cornell University

Quantum materials research aims to uncover exotic physics and new approaches toward applied technologies. Two-dimensional crystals consisting of individual layers of van der Waals materials provide an exciting platform to study correlated and topological electronic states. These same crystals can be flexibly restacked into van der Waals heterostructures, which enable clean interfaces between heterogeneous materials. Such heterostructures enable the isolation and protection of air-sensitive 2D materials as well as provide new degrees of freedom for tailoring electronic structure and interactions. In this talk, I will present experimental work studying electronic transport in monolayer WTe2. First, un-doped monolayer WTe2 exhibits behaviors characteristic of a 2D topological insulator, including edge mode transport approaching the quantum of conductance up to nearly 100 Kelvin. Second, we have discovered that the same monolayers display superconductivity at low carrier densities accessible by local field-effect gating through a low-κ dielectric. The concurrence of electrostatically accessible superconductor and topological insulator phases in the same 2D crystal allows us to envision a new model of gate-configurable topological electronic devices.

Signatures of Spin and Coulomb interactions in the Andreev spectrum of nanowire superconducting weak links

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The flow of Josephson supercurrent through a non-superconducting material connecting two superconductors is governed by quasiparticle states localized at the "weak link": the Andreev bound states. The energy of these fermionic states depends on the phase difference between the superconductors, and their occupation determines the electronic properties of the weak link. I will present experiments on semiconducting nanowire weak links performed with circuit Quantum Electrodynamics techniques [1,2,3]. The high resolution spectra of Andreev Bound States reveal the effects of spin-orbit coupling [1,2] and of Coulomb interactions among quasiparticles [3].

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Current-Phase Relation of hole-type Ge/Si Core/ Shell Nanowire Josephson Junctions

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Interest in group IV materials for quantum information technologies is continuously increasing, in particular for CMOS compatible germanium-based systems [1]. Holes in germanium hold excellent properties like reduced hyperfine interaction and strong and electrically tunable "direct" Rashba spin-orbit interaction (SOI) [2].

The current-phase relationship (CPR), as one of the most fundamental properties of a Josephson junction, contains information about the Andreev bound state (ABS) spectrum in the weak link [3] and can serve as a powerful tool to explore the physical phenomena like electron-electron interactions [4], band topology [5], or SOI [6]. Until now, CRP measurements have been reported in several material platforms, like InAs nanowires with epitaxial aluminum shells [7], ballistic graphene [8], magnetic junctions [9], or topological Bismuth nanowires [10]. Despite the growing attention on germanium-based platforms, corresponding CPR measurements are largely missing, with few exceptions on Ge based 2D platforms [11,12]. Here we report CPR measurements for two Josephson junctions based on Ge/Si core/shell nanowires, embed in a superconducting quantum interference device (SQUID) geometry. The Josephson junction is fabricated by annealing Al into the Ge core [13]. With electrical side gates, we can individually tune the critical current in each arm. In an asymmetrical supercurrent configuration, we find a non-reciprocal critical current when changing the current bias direction, often described as Josephson diode effect [14]. Most intriguingly, we find an anomalous CPR with a non-sinusoidal component at selected gate voltages, an effect we currently investigate in more detail. These results establish Ge/Si core/shell nanowires as a platform to investigate superconductor–semiconductor hybrid physics with large gate-tunable SOI, paving the way for potential applications like, for example, Andreev spin qubits [15] with enhanced qubit coherence times.

Current-Phase Relation of hole-type Ge/Si Core/ Shell Nanowire Josephson Junctions - References.

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Cooper pair splitting and Andreev molecule in Superconductor - Parallel InAs nanowire hybrid

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Hybrid nanostructures consisting of two parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available [1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can be utilized to enhance crossed Andreev reection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow not only a highly-efficient spatial separation of entangled electrons in the so-called Cooper pair splitting process (CPS) [2], but can lead to the strong hybridization of the QDs resulting in an Andreev molecule [3], as a milestone towards more exotic states, like Majoranna or parafermions [4]. We report the experimental realization of both CPS and Andreev molecule in different parallel nanowire-based nanocircuits (see Fig. 1). We characterize the electrostatic and the CAR-mediated interaction between parallel QDs. Furthermore, we also present the expected response of an Andreev molecule when it is placed between two superconducting electrodes. The supercurrent has strongly non-local character, like tun[]able phi_0 phase, or 0 pi shift within the same groud state [5].

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Microwave spectroscopy of spin-split Andreev levels in a quantum dot

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I will discuss recent measurements of quantum dot Josephson junctions embedded in a transmon circuit [1-2]. Dispersive readout allows one to detect the singlet-doublet transition of the proximitized quantum dot and, in the doublet state featuring a trapped quasiparticle in the dot, to extract the phase dispersion of Andreev levels. The latter measurements reveal the role of spin-orbit coupling in splitting the energy levels of the trapped quasiparticle. The measurements are interpreted theoretically on the basis of a simple Anderson model, with reasonable success. I will discuss implications and perspectives for Andreev spin qubits.

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Supercurrent diodes and magnetochiral anisotropy in ballistic Josephson junctions

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The recent discovery of intrinsic supercurrent diode effect [1], and its prompt observation in a rich variety of systems, has shown that nonreciprocal supercurrents naturally emerge when both space- and time-inversion symmetries are broken. I will report on ac- and dc-manifestations of the diode effect in planar Josephson junctions, based on a ballistic Al/InAs-heterostructure that is exposed to an in-plane magnetic field Bip [3]. Measurement of the non-linear inductance provide a complete characterization of the junctions parameters [2]. It is shown that the transverse field Bip can lead to cosine terms in the current phase relation (CPR), if the latter also displays higher harmonics. At low Bip a non-reciprocal term is found in the CPR that is linear in Bip. At higher Bip a sign reversal of the magnetochiral term is observed that can be traced back to a 0-pi-like transition in the current-phase relation. Thus inductance measurements reveal deep insights into the interplay of different types of symmetry breaking in our junctions.

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Gralmonium: Granular aluminium nanojunction fluxonium qubit

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Mesoscopic Josephson junctions, consisting of overlapping superconducting electrodes separated by a nanometre-thin oxide layer, provide a precious source of nonlinearity for superconducting quantum circuits. Here we show that in a fluxonium qubit, the role of the Josephson junction can also be played by a lithographically defined, self-structured granular aluminium nanojunction: a superconductor–insulator–superconductor Josephson junction obtained in a single-layer, zero-angle evaporation. The measured spectrum of the resulting qubit, which we nickname gralmonium, is indistinguishable from that of a standard fluxonium. Remarkably, the lack of a mesoscopic parallel plate capacitor gives rise to an intrinsically large granular aluminium nanojunction charging energy in the range of tens of gigahertz, comparable to its Josephson energy. We measure coherence times in the microsecond range and we observe spontaneous jumps of the value of the Josephson energy on timescales from milliseconds to days, which offers a powerful diagnostics tool for microscopic defects in superconducting materials.

Observation of a Kondo impurity and its universal screening using a charge pseudospin

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The Kondo effect, deriving from a local magnetic impurity mediating electron-electron interactions, constitutes a flourishing basis for understanding a large variety of intricate many-body problems. Its experimental implementation in tunable circuits has made possible important advances through well-controlled investigations. However, these have mostly concerned transport properties, whereas thermodynamic observations - notably the fundamental measurement of the spin of the Kondo impurity - remain elusive in test-bed circuits. Here, I will present an observation of the state of a Kondo impurity and its progressive screening thanks to a novel implementation of a 'charge' Kondo circuit [1]. In our device, a Kondo pseudospin is realized by two degenerate charge states of a metallic island, which we measure with a non-invasive, capacitively coupled charge sensor. With this approach, we establish the universal renormalization flow from a single free spin to a screened singlet, the associated reduction in the magnetization, and the relationship between scaling Kondo temperature and microscopic parameters [2].

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Entanglement Shell Structure of Multichannel Kondo Cloud

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An essential concept of quantum impurity problems is the quantum coherent screening of the impurity. In this work, we theoretically analyze the screening of the impurity spin by using quantum entanglement. We develop a method to compute the entanglement negativity between the impurity and its environment in spin-1/2 impurity problems, based on the boundary conformal field theory and numerical renormalization group. We apply our method to the multi-channel Kondo model, a strongly correlated system in which conduction electrons of multiple channels compete to screen one impurity, to unveil the spatial structure of Kondo screening cloud. We find that the Kondo cloud has a universal power-law tail and the tail has a hierarchical entanglement shell structure in the anisotropic multi-channel Kondo effects. The shell structure originates from competition between the channels in Kondo impurity screening, and it corresponds to distinct non-Fermi liquid phases of multi-channel Kondo effects. Shells of distinct non-Fermi liquids coexist in the structure. As temperature increases, the shells become suppressed one by one from the outside, and the remaining outermost shell determines the thermal phase of each channel. We propose how to observe the entanglement and the Kondo cloud shell structure profile, based on a charge Kondo setup.

Quantum Computation - Spins Inside

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Quantum computation has captivated the minds of many for almost two decades. For much of that time, it was seen mostly as an extremely interesting scientific problem. In the last few years, we have entered a new phase as the belief has grown that a large-scale quantum computer can actually be built. Quantum bits encoded in the spin state of individual electrons in silicon quantum dot arrays, have emerged as a highly promising direction [1]. In this talk, I will present our vision of a large-scale spin-based quantum processor, and ongoing work to realize this vision. First, we created local registers of spin qubits with sufficient control that we can program arbitrary sequences of operations, implement simple quantum algorithms [2], and achieve two-qubit gate fidelities of more than 99.5% [3]. In linear quantum dot arrays, we now achieve universal control of up to six qubits with respectable fidelities for initialization, readout, single- and two-qubit operations [4]. Second, we have explored coherent coupling of spin qubits at a distance via two routes. In the first approach, the electron spins remain in place and our coupled to each other via a microwave photon in a superconducting on-chip resonator [5,6]. In the second approach, spins are shuttled along a quantum dot array, preserving the spin state [7,8]. Third, in close collaboration with Intel, we have fabricated and measured quantum dots using all-optical lithography on 300 mm wafer, using industry-standard processing [9], demonstrating excellent qubit performance. We expect that this industrial approach to nanofabrication will be critical for achieving the extremely high yield necessary for devices containing thousands of qubits. When combined, the progress along these various fronts can lead the way to scalable networks of high-fidelity spin qubit registers for computation and simulation.

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A single hole spin with enhanced coherence in natural silicon

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Semiconductor spin qubits based on spin-orbit states stand as promising candidates in view of developing a quantum processor. Owing to their strong spin-orbit interaction, hole spins in silicon [1] and germanium [2] are responsive to electric field excitations, allowing for practical, fast and potentially scalable qubit control. As a drawback, spin electric susceptibility renders these qubits generally vulnerable to electrical noise, which limits their coherence time. Here we report on the operation and readout of a single hole spin in natural silicon, made from a semi-industrial 300 mm CMOS foundry. We demonstrate the existence of a preferential magnetic field orientation, at which the qubit is decoupled from charge noise while keeping an efficient electrical control.We first realize spin single-shot readout [3] of the first hole accumulated in a silicon quantum dot. Subsequently, we characterize the hole spin gyromagnetic tensor and its susceptibility to electric fields by coherent manipulation techniques. We evidence a strong dependence on the external magnetic field orientation, and reveal optimal operation points at which the longitudinal spin-electric susceptibility is minimal. At these sweet spots, we measure a Hahn-Echo decay time in the order of 100 µs while maintaining Rabi frequencies in the MHz range. This work opens new perspectives for quantum processing based on spin-orbit qubits.

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Coherent shuttling of hole spin states in a germanium quantum dot array

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The coupling of distant qubits or quantum processors presents clear advantages for the implementation of modular, fault-tolerant and large scale quantum computers. Such long-distance coupling can be implemented in semiconductor spin qubits by shuttling coherently spin states between neighbour quantum dots. Long distance and coherent electron spin state transports via shuttling have been demonstrated in GaAs [1-3] and in silicon [4,5] and have already enabled the implementation of quantum operations between distant spin qubits [6]. In this work, we investigate coherent hole spin shuttling in germanium quantum dot arrays, a promising alternative platform that has recently emerged [7]. We demonstrate the coherent transfer of superposition spin states in a 2x2 germanium quantum processor [8], in different directions and over several sites. We also report the observation of coherent spin oscillations appearing while transferring holes with pure spin-up/down states and show that they witness large changes in the direction of quantization axis between adjacent quantum dots. We discuss the implications of these findings on the shuttling operation and its performance. Our results provide new insights on the physics of hole spin qubits in semiconductors and open new perspectives for the implementation of large scale quantum computer based on spin qubits in germanium.

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Neon

Single electrons on solid neon: a long-coherence high-fidelity solid-state qubit platform

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Progress towards the realization of quantum computers requires persistent advances in their constituent building blocks – qubits. Novel qubit platforms that simultaneously embody long coherence, fast operation, high fidelity, and large connectivity offer compelling advantages in the construction of quantum computers. Electrons, ubiquitous elementary particles of non-zero charge, spin and mass, have commonly been perceived as paradigmatic local quantum information carriers. Despite superior controllability and configurability, their practical performance as qubits through either charge (motional) or spin states depends critically on their material environment. In this talk, I will present our experimental realization of a new qubit platform based upon isolated single electrons trapped on an ultraclean solid neon surface in vacuum. By integrating an electron trap in a superconducting quantum circuit, we achieve strong coupling between the charge states of a single electron and a single microwave photon in an on-chip resonator [1]. Qubit gate operations and dispersive readout are successfully implemented. The measured relaxation time T1 and coherence time T2 are both on the order of 0.1 milliseconds [2]. The single-shot readout fidelity without relying on a quantum-limited amplifier is 98.1%. The average single-qubit gate fidelity using Clifford-based randomized benchmarking is 99.97%. Simultaneous strong coupling of two qubits with the same resonator is demonstrated, as a first step toward two-qubit entangling gates for universal quantum computing. These results manifest that the electron-on-solid-neon (eNe) charge qubits outperform all existing charge qubits to date and rival state-of-the-art superconducting transmon qubits, offering an appealing platform for quantum computing.

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Mechanical oscillators

Schrödinger cat states of a 16-microgram mechanical oscillator

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One of the fundamental unanswered questions in quantum physics is why we do not observe macroscopic objects to be in superpositions of states that can be distinguished by some classical property. Various experiments have tried to explore this question by creating so-called «Schrödinger cat states» in systems ranging from SQUIDs to atom interferometers. I will present our recent work that demonstrates the preparation of a mechanical resonator with an effective mass of 16 micrograms in Schrodinger cat states of motion, where the constituent atoms oscillate in a superposition of two opposite phases. By using the resonant Jaynes-Cummings interaction between the resonator mode and a superconducting qubit, we are able to demonstrate the evolution of an initial mechanical coherent state into a superposition of distinct states in phase space. Our results may have applications in continuous variable quantum information processing and in fundamental investigations of quantum mechanics in massive systems.

Quantum Error Correction for Superconducting Quantum Processors*

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Superconducting electronic circuits are ideally suited for studying both the foundations of quantum physics and its applications. Since complex circuits combining hundreds or thousands of circuit elements can be designed, fabricated, and operated with relative ease, superconducting quantum circuits are one of the prime contenders for realizing quantum computers. For fault-tolerant operation, universal quantum computers must correct errors occurring due to limited control accuracy and unavoidable decoherence. Therefore, quantum error correction is a prime target of current research and development across academia and industry. Recently, our Quantum Device Lab at ETH Zurich has demonstrated quantum error correction in the surface code. Using 17 physical qubits in a superconducting circuit we encode quantum information in a distance-three logical qubit. In an error correction cycle of only 1.1 µs duration, we demonstrate the preservation of four cardinal states of the logical qubit with a logical error probability of only 3 % per cycle [1]. In the process, we detect both bit- and phase-flip error syndromes and decode using a minimum-weight perfect-matching algorithm in an error-model-free approach. In this talk, I will discuss characteristic error syndromes and their effect on the performance of our implementation of the surface code. One of the dominant errors limiting the performance of quantum error correction codes across multiple technology platforms is leakage out of the computational subspace, originating from the inherent multi-level structure of many qubit implementations. Therefore, I will discuss our recent experimental progress in effectively mitigating leakage errors in superconducting circuits. The demonstration of repeated, fast, and high-performance quantum error correction, and the continued improvement of device performance supports our understanding that fault-tolerant quantum computation will be practically realizable.

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*This work was done in collaboration with Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler, and Andreas Wallraff.

Single electron-spin-resonance by microwave photon counting

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Electron spin resonance (ESR) spectroscopy is the method of choice for characterizing paramagnetic impurities in a sample, with applications ranging from chemistry to quantum computing but it gives access only to ensemble-averaged quantities due to its limited signal-to-noise ratio. Here, we report a new method for the detection of single electron spins at millikelvin temperatures. Analogous to the optical fluorescence detection of atoms or molecules, it consists in detecting the microwave photons spontaneously emitted by an electron spin when it relaxes radiatively to its equilibrium ground state after being excited by a pulse [1]. To enhance the radiative relaxation rate [2], the spins are inductively coupled to a small-mode-volume, high-quality-factor, superconducting resonator patterned on top of the sample. The microwave fluorescence photons are then routed towards a single-microwave-photon counter based on a superconducting qubit [3].

The method applies to all paramagnetic species with sufficiently low non-radiative decay rate; here, we demonstrate it on rare-earth-ion spins (Er3+) doped in a scheelite CaWO4 host matrix. We resolve individual narrow peaks in the fluorescence signal, on which we observe microwave photon anti-bunching, proving that they originate from single spins [4]. We reach a signal-to-noise ratio of 1 in 1 second integration time for each Er3+ ion located in a detection volume of ~20µm3. We observe spin coherence times above a millisecond, limited by the radiative lifetime. I will discuss the new perspectives opened by these results for practical single-electron spin resonance spectroscopy and spin-based quantum computing.

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Continuous monitoring of cavity photon number

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It is possible to count the number of photons in a microwave cavity by exploiting the dispersive interaction between a superconducting qubit and the cavity. In standard protocols, it requires to perform a series of gates on the qubit that are conditioned on the cavity occupation, followed by readout operations on the qubit using an ancillary readout resonator [1–3]. Recently, our group introduced a way to realize this counting by multiplexing the driving tones on the qubit and continuously extracting information about the number of photons. A previous experiment managed to show that the counting works on average on many realizations of the experiment and that the coherences between Fock states disappear as expected when the drive is turned on [4]. In this work, we use a new device that is able to resolve the photon number in a single realization of the experiment. The cavity is a high-quality factor 3D superconducting cavity whose lifetime is above 250 µs. A carefully designed filter allows us to drive and measure the emitted field by the qu-bit at a rate, which is orders of magnitude larger than the decay rate of the cavity. The simultaneous heterodyne detection of the fluorescence field that this qubit emits at all frequencies reveals the photon number in the cavity and produces a quantum backaction on the cavity state. This measurement enables the characterization of the measurement rate of the photon number and of the photocounting fidelity. Looking forward, we plan to use this experimental platform to first demonstrate high fidelity preparation of Fock states in the cavity, and then their stabilization using continuous measurement-based feedback. Neural networks will be used to train the feedback control.

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Characterization of the disorder in a mesoscopic sample from quantum transport properties using machine learning

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Gaëtan Percebois, Antonio Lacerda-Santos, Xavier Waintal, Dietmar Weinmann

Different microscopic disorder realizations lead to uncontrolled sample-to-sample fluctuations in the electronic quantum transport properties of nanoscale devices. We develop a method to determine the disorder potential seen by the electrons from experimentally accessible information on the quantum transport properties of the sample. The approach is based on the numerical simulation of the transport properties for a large number of disorder configurations, and the use of the resulting dataset to train a deep neural network to solve the inverse problem. To obtain the full disorder potential landscape, we use transport data with spatial resolution. For a model of a quantum point contact in a two-dimensional electron gas we have shown that it is possible to extract the disorder potential from the simulated partial local density of states (PLDOS) with a rather high precision [1]. To detect the disorder potential in a real sample, we train an artificial intelligence with simulated scanning gate microscopy (SGM) data, corresponding to the conductance as a function of the position of a charged tip above the surface of the sample. The realistic simulation of SGM data, including the electrostatic environment of the sample [2], is much more costly in computational resources than the one of the PLDOS for a simplified model, leading to a limited size of the available dataset for the training of our artificial intelligence. The situation is improved using transfer learning and data augmentation techniques.

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Statistics of Broadband Microwave Photons

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Much effort has been put in the conception and fabrication of large bandwidth amplifier such as travelling-wave parametric amplifiers and quasi-particle based SIS junctions. With such device, we can expect new interesting state such as large bandwidth squeezed states to be achievable in the lab, and new measurement tools will be necessary to correctly describe their quantum nature. In this work, we describe how to recover large bandwidth photon statistics from continuous operator measurement in the microwave domain. The proposed solution involves the use of time domain quadrature which are approximated using an on the fly numerical transformation of the 32GSa/s voltage samples. Crucially we show that a large bandwidth photon detector does not correspond, as one might expect, to the sum of monochromatic photo detectors over the same bandwidth. The proposed measure leads to photon statistics no matter if the chosen photon basis is narrow or large in bandwidth. This work has been supported by the Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Innovation.

Anyonic statistics and scaling dimension revealed by the Hong-Ou-Mandel dip and photo-assisted transport in the fractional quantum Hall effect

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The fractional quantum Hall effect (FQHE) is known to host anyons, quasiparticles whose statistics is intermediate between bosonic and fermionic. We show here that Hong-Ou-Mandel (HOM) interferences between excitations created by narrow voltage pulses on the edge states of a FQHE system at low temperature show a direct signature of anyonic statistics. The width of the HOM dip is universally fixed by the thermal time scale, independently of the intrinsic width of the excited fractional wavepackets. This universal width can be related to the anyonic braiding of the incoming excitations with thermal fluctuations created at the quantum point contact. We show that this effect could be realistically observed with periodic trains of narrow voltage pulses using current experimental techniques. We also study photo-assisted current using a Keldysh-Floquet approach, when the AC drive is applied either directly to the edge states, or when it modulates the tunneling amplitude at the quantum point contact. Strikingly, for a simple cosine modulation of the tunneling amplitude, the phase shift of the second harmonic of the photoassisted current is directly related to the scaling dimension of the quasiparticle operators describing the fractional excitations.

Two-particle time-domain interferometry in the Fractional Quantum Hall Effect regime

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Quasi-particles are elementary excitations of the ground state of condensed matter quantum phases. Demonstrating that they keep quantum coherence while propagating is a fundamental issue for their manipulation for quantum information tasks. This is particularly the case for the quasi-particles called anyons of the Fractional Quantum Hall Effect (FQHE). These fractionally charged quasi-particles obey anyonic statistics intermediate between fermionic and bosonic. Their quantum coherence has been observed by their transmission through the localized states of electronic Fabry-Pérot interferometers. Surprisingly, no or very weak quantum interference of anyons was observed in electronic Mach-Zehnder interferometers for which the quasi-particle transmission occurs via propagating states. Here, we show that FQHE anyons do keep a finite quantum coherence while propagating by using a novel kind of interferometry, namely two-particle time-domain interference [1] using an electronic beam-splitter. By varying the time delay between photo-created electron-hole pairs and measuring cross-correlated noise sensitive to the twoparticle Hanbury Brown Twiss (HBT) phase [1], we observe strong quasiparticle interference [2]. At bulk filling factor 2/5, visibilities as high as 53% and 60% are observed for e/5 and e/3 charged propagating anyons, probably limited by copropagating channel mixing [3]. At bulk filling factor 2/3 a similar large quantum coherence is observed for the 2/3 edge channel.

I. Taktak, M. Kapfer, J. Nath, P. Roulleau, M. Acciai, J. Splettstoesser, I. Farrer, D. A. Ritchie, D. C. Glattli; Nat Commun 13, 5863 (2022)

Quantum sensing of time dependent electromagnetic fields with single electron excitations

Pascal Degiovanni
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In this talk, I will discuss the potential of electronic interferometers for probing the quantum state of electromagnetic radiation on a chip at sub-nanosecond time scales. We propose to use single electron excitations propagating within an electronic Mach-Zehnder interferometer in the Aharonov-Bohm dominated regime.

We will discuss how information about the quantum state of the electromagnetic radiation is encoded into the interference contribution to the average outgoing electrical current. Furthermore, we present specific examples showing that our method has the potential to measure properties of quantum radiation in both the time and frequency domains. We finally discuss how shaping techniques of single electron wave-packets can be used to obtain the strongest signal associated with the external radiation. The development of these techniques could have significant implications for probing the fundamental properties of electromagnetic radiation on short time scales in the microwave and tera-Hertz domains.

Comparing fractional quantum Hall Laughlin and Jain topological orders with the anyon collider

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LPENS Paris

Anyon collision experiments have recently demonstrated the ability to discriminate between fermionic and anyonic statistics. However, only one type of anyons associated with the simple Laughlin state at filling factor ν=1/3 has been probed so far. It is now important to establish anyon collisions as quantitative probes of fractional statistics for more complex topological orders, with the ability to distinguish between different species of anyons with different statistics. In this work, we use the anyon collider to compare the Laughlin ν=1/3 state, which is used as the reference state, with the more complex Jain state at ν=2/5, where low energy excitations are carried by two co-propagating edge channels. We demonstrate that anyons generated on the outer channel of the ν=2/5 state (with a fractional charge e*=e/3) have a similar behavior compared to ν=1/3, showing the robustness of anyon collision signals for anyons of the same type. In contrast, anyons emitted on the inner channel of ν=2/5 (with a fractional charge e*=e/5) exhibit a reduced degree of bunching compared to the ν=1/3 case, demonstrating the ability of the anyon collider to discriminate not only between anyons and fermions, but also between different species of anyons associated with different topological orders of the bulk. Our experimental results for the inner channel of ν=2/5 also point towards an influence of interchannel interactions in anyon collision experiments when several co-propagating edge channels are present.

Coulomb-mediated antibunching of an electron pair surfing on sound

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J. Wang,, H. Edlbauer, A. Richard, S. Ota, W. Park, J. Shim, A. Ludwig, A. D. Wieck, H.-S. Sim, M. Urdampilleta, T. Meunier, T. Kodera, N.-H. Kaneko, H. Sellier, X. Waintal, S. Takada, C. Bäuerle1

A surface acoustic wave (SAW) can transfer a single electron via a surface-gate-defined channel between distant quantum dots with very high fidelity [1,2]. This acousto-electric transport technique offers an original platform for quantum-optics-like experiments with single flying electrons exploiting their spin [3] or charge degree of freedom [4,5]. Here we present a SAW-assisted single-electron circuit that consists of two tunnel-coupled transport channels and perform investigations on electron-electron interaction via Hong-Ou-Mandel (HOM) interferometry [6]. We transfer a pair of flying electrons from independent sources towards a coupling region calibrated at half transmission. Employing a triggered-sending process, we control the synchronization between the electrons that allows us to contrast the full-counting statistics of the single-shot events with and without interaction. Only when the electron pair is synchronized, we observe an excess in the probability P11 (arrival of one electron at each detector) up to 30% (see Fig. 1b). To unveil the underlying interference mechanism, we perform numerical simulations where Coulomb interaction plays the dominant role. The presented investigation sheds light on the in-flight electron-electron interaction and thus paves the way to implement controlled phase gates in electron-quantum-optics experiments driven by sound. If time allows, I will also briefly highlight our recent results on SAW wave engineering for scalable single-electron transport [7].

[1] Hermelin et al., Nature 477, 435–438 (2011). [2] McNeil et al., Nature 477, 439–442 (2011). [3] Jadot et al., Nat. Nanotechnol. 16, 570–575 (2021). [4] Bäuerle et al., Rep. Prog. Phys. 81, 056503 (2018). [5] Takada et al., Nat. Commun. 10, 4557 (2019). [6] Wang et al., arXiv:2210.03452v1 accepted for publication in Nature Nanotechnology. [7] Wang et al., Phys. Rev. X 12, 031035 (2022) and highlight in PHYSICS

Quantum dot pump coupled with a single quantum Hall edge Kind

Wanki Park
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Development of single-electron sources is a crucial step towards a fermion version of quantum optics and a solid-state quantum processing [1,2]. Further development of single-electron sources is desired, since existing sources do not cover the emission energy range of 1 – 60 meV. We theoretically and experimentally propose a new type of a single-electron source [3], which is composed of an interacting quantum dot and a single lead. As the quantum dot is coupled to the single lead (a chiral quantum Hall edge), electron-hole pairs are pumped by AC modulation of the quantum dot. The energy of pumped electrons can be 10 - 60 meV with help of the charging energy in the quantum dot while the hole energy is near the Fermi energy. Utilizing the energy separation, the electron and the hole of a pumped pair are spatially split by applying a tunable-potential barrier located on the path of the pumped pair. We theoretically describe the pumping mechanism using a master equation. We find that the single-electron generation resulting from the pumping and splitting of the electron-hole pairs is identified by characteristic triangular shape regions in the pump map. Our single-electron source is experimentally realized, and the obtained pump map is in good agreement with the theoretical result.

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[2] M. D. Blumenthal et al., Nat. Phys. 3, 343 (2007)
[3] S. U. Cho et al., Nano. Lett. 22, 9313 (2022)

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Photon emission by hot electron injection across a lateral PN junction

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National Physical Laboratory

It was proposed that on-demand single photon source could be constructed by a combination of single-electron source [1] and lateral PN junction [2]. Hot electrons emitted by single-electron source could have energy high enough to overcome PN junction barrier and recombine with holes in the p-type region followed by photon emission. However, hot electrons are likely to lose their energy on a trajectory to the PN junction a few microns away from the source. It is known that optical phonon emission is a major process for hot electrons to lose their energy [3]. A method to transport hot electrons into a p-type region needs to be developed. We generate hot electrons with a potential barrier and biasing, and then guide them into a PN junction. We observe that hot electrons are injected into p-type region and recombine with holes emitting photons using hot-electron energy spectroscopy and optical spectroscopy. Our results show that hot electrons can travel a distance of a few microns between hot electron source and PN junction, which presents the way towards on-demand single photon source.

[1] M. Blumenthal et al., Nature Phys 3, 343 (2007).
[2] Van-Truong Dai et al., Optics Express 22, 3811 (2014).
[3] D. Taubert et al., Phys Rev. B 83, 235404 (2011).

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Spectroscopy of hot-electron pair emission from a driven quantum dot

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Controlled emission of single electrons as well as of few-electron states is an important ingredient of electronic quantum technologies. One possibility to realise this is via barrier-driven quantum dots emitting so-called "hot electrons" into a conductor far above the Fermi sea. For applications in quantum technologies not only the precision of the emission in time is relevant, but also the emission energy needs to be well-controlled.

In this talk, I will address the energetics of the emission process of a pair of electrons from a driven quantum dot and present results from an in-depth theoretical analysis (based on numerical simulations as well as a time-dependent master equation) [1]. When driving such a quantum dot by modulating in time the single-electron energies as well as the coupling strength, the emission times and energies of the two emitted electrons differ. We identified that a quantum-dot model that captures the main competing effects needs to involve states that possibly differ with respect to their spatial distribution, a local Coulomb interaction, as well as energy-dependent couplings to the conductor. I will show how the state-degeneracy, the internal dynamics of the dot together with the state-dependent coupling, as well as the strong interaction influence the difference in emission time and energies for different time-scales of the gate modulation. Our results provide insights to guide the development for single-electron sources with high control over emission energies

[1] Jens Schulenborg, John Fletcher, Masaya Kataoka, and Janine Splettstoesser, in preparation.

Chiral Luttinger liquid behavior in a graphene fractional quantum Hall point contact: from universal conductance scaling to Andreev scattering of e/3 quasiparticles

Liam Cohen
UCSB

One dimensional conductors are described by the theory of Luttinger liquids, a non-Fermi liquid state characterized by a power law suppression of the tunneling density of states near the Fermi level which goes as (E - EF)1/g -1. This manifests experimentally in the tunneling conductance which should exhibit power-law behavior with exponent "1/g-1" in both voltage bias and temperature. While in general "g" is a non-universal parameter determined by the details of the inter-mode interactions in the wire, the edge states of the fractional quantum Hall (FQH) effect provide a unique 1D system in which "g» becomes quantized as a result of the edge bordering a topologically non-trivial bulk. Using a graphene quantum point contact made entirely of van der Waals materials, we directly interface the ν = 1/3 and ν = 1 edges at a single point and study the resulting tunneling characteristics. We demonstrate, in the weak tunneling limit, universal scaling behavior of the conductance consistent with the prediction that g = ν = 1/3. In the opposite limit, surprisingly, at large bias voltages and temperatures, or as the QPC becomes more open, we observe that the conductance saturates to 1/2 e2/h. Additionally, whenever the conductance exceeds 1/3 e2/h, a negative voltage downstream of the QPC develops. This result can be attributed to the Andreev-like reflection of incoming e/3 quasiparticles at the point contact. We exploit this process to realize a nearly dissipation-free D.C. voltage step-up transformer, which has a maximum integrated gain of 1.45 and power efficiency of 97%. This result implies that the heterojunction can be made nearly adiabatic, demonstrating a significant improvement in the state-of-the-art for quantum Hall mesoscopic devices.

Anyonic exchange in a quantum point contact

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Under strong magnetic fields, electrons that are confined to two spatial dimensions can exhibit a fractional quantum Hall state where the elementary particles carry only a fraction of the electron charge. These exotic excitations, called anyons, moreover behave under the interchange of two individuals neither as fermions nor as bosons but are characterized instead by a non-trivial exchange phase. The experimental proof of these anyons and their exchange phase was performed only recently, in 2020.

Recent experiments have demonstrated in particular that a quantum point contact on the edge channels of a fractional quantum Hall (Laughlin) state is able to reveal the anyonic phase from noise measurements. Here, we show how the information about braiding governs the output noise correlations. We identify the incoming fractional signal as an environment for the beam splitter with an interference between the two input edge channels. The tunneling at the quantum point contact is triggered by this environment and involves a space-time braiding between the tunneling anyon and the incoming quasiparticles. We also discuss the effect of non-linearity in the tunneling and distinguish it from braiding.

Mesoscopic Heat 'Multiplier' - A Quantum Hall device revealing correlated States

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Local measurements of the heat flux in Quantum Hall devices can differ from the expected equilibrium heat flux due to interactions. We model a simple mesoscopic device like a mesoscopic collider, consisting of ohmic reservoirs connected via chiral edge states. In an internal edge state of the device, the interaction between the reservoirs leads to extra correlations adding to the, locally measured, equilibrium heat flux. We investigate how these correlated states can be detected, discuss their thermometry and how one could reveal their nature experimentally through interference experiments or cross correlation measurements. The latter are sensitive to the nature of the multiplication/fractionalization and can distinguish statistical effects from interaction effects.

Noise signatures of Anyon statistics and Andreev scattering in the nu=1/3 fractional quantum Hall regime

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Anyons are exotic quasiparticles which can carry a fractional charge of an electron and with an exchange statistics in between that of fermions and bosons. These properties were revealed using quantum point contacts (QPC) in the fractional quantum Hall regime [1,2,3].

In this talk, I will report further noise investigation of anyon physics. Sourcing e/3 anyons at a first QPC, noise measured on a downstream «»analyzer»» QPC reveals different mechanisms. Setting the analyser to allow e/3 tunneling charges, we reproduce the negative cross-correlations previously observed [2], indicative of a non-trivial anyon exchange phase [4]. When 1 e charges tunnel across the analyser, the braid phase is predicted to be trivial. Our observation of negative cross-correlations points on a scattering mechanism akin to Andreev reflection at Normal/Superconductor interfaces, as suggested in [5]. Remarkably, in both cases, electrical conduction across the analyzer conserves neither the nature nor the number of quasiparticles, rending the beam-splitter analogy of a QPC lapsed.

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[3] J. Nakamura et al., Nat. Phys. 16, 931-936 (2020)
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Non-Abelian Anyon Collider

June-Young Lee
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Anyon is an exotic quasiparticle that is neither fermion nor boson. On top of long time efforts to detect the anyonic statistics in the fractional quantum Hall (FQH) systems, there was a recent experimental breakthrough on the Abelian anyon collider at a Laughlin state [1], in agreement with the non-equilibrium bosonization theory [2]. However, it remains elusive which aspect of the anyonic statistics is identified from the experimental results, and there is even no theoretical prediction for the non-Abelian anyons.

Here we develop a theory of anyon colliders on the generic FQH systems, that is applicable for both Abelian and non-Abelian anyons [3]. Based on a conformal field theory and non-perturbative resummation over all perturbation orders of anyon injection to the collider, we predict that the collider provides a tool for direct observation of the braiding statistics of various Abelian and non-Abelian anyons. Its dominant process is not direct collision between the injected anyons, contrary to common expectation, but a time-domain interference that an anyon excited at the collider braids with the injected anyons. Our finding implies that the collider experiments including Ref. [1] actually provide a direct signature of the anyon braiding.

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[2] B. Rosenow, I. P. Levkivskyi, and B. I. Halperin, Current Correlations from a Mesoscopic Anyon Collider, Phys. Rev. Lett. 116, 156802 (2016).
[3] June-Young M. Lee, and H.-S. Sim, Non-Abelian Anyon Collider, Nat. Commun. 13, 6660 (2022).

Charge-conserving equilibration of quantum Hall edge states

Eugene Sukhorukov
University of Geneva

We address the problem of the equilibration of quantum Hall (QH) edge states under the additional constraint of charge conservation.This question applies generally to any chiral quasi-one dimensional states, but it naturally arises in the context of resent experiments with quantum Hall systems. This is because QH edge states carry charge excitations with approximately constant speed, and in a typical mesoscopic experiment, to finite distances. Therefore, edge states dynamics must depend on the initial generally non-equilibrium state via boundary condition. Thus even in the case of a strong coupling of edge states to the bath of neutral excitations, their complete equilibration is often not possible. In order to investigate the equilibration process under such conditions, we propose the model describing QH edge states as a chiral bosonic channel strongly coupled to an array of identical Ohmic contacts with small capacitances. Such model effectively describes a chiral one-dimensional charged channel with dissipation. Asymptotically close to the equilibrium state, the electron distribution function acquires an almost equilibrium form with the universal correction, which is a function of the energy and distance form the injection point, where a non-equilibrium state is created.

UltraFastNano

Andrea Hoffmann
University of Basel

On-demand Coulomb collisions at a mesoscopic beamsplitter: the non-linear limit of electron quantum optics

Vyacheslavs Kashcheyevs
University of Latvia

Experimental progress in on-demand generation and high-fidelity detection of individual ballistic electrons in depleted semiconductor nanostructures opens new regimes for probing interactions in quantum optics. I will discuss the quantum non-linear regime where the coincident presence of a second particle at the beamsplitter changes the transmission for the first. I will report on experimental results from collaboration led by the German National metrology institute PTB. Coincidence correlations revealed by the full counting statistics demonstrate the classical counterpart of the Hon-Ou-Mandel effect with few-picosecond scale resolution. Characteristic signatures of large energy exchange validate a microscopic model of Coulomb collision of two chiral electrons – a low-dimensional analogue of the Rutherford scattering experiment. Applications to flying qubit readout and single-electron wave-packet tomography will be discussed.

Ultrafast carrier dynamics in graphene

Norio Kumada
NTT Basic Research Laboratories

We investigate ultrafast carrier dynamics in two-dimensional materials using on-chip THz spectroscopy. In this talk, I will mainly present our findings regarding optical-to-electrical conversion in graphene photodetectors [1]. We excite graphene by femto-second laser pulse and read the photothermoelectric current with the time resolution better than 1 ps. By comparing the photocurrent response for various Fermi energies in samples with different geometry and mobility, we obtained a comprehensive understanding of the optical-to-electrical conversion mechanisms in graphene. These insights are crucial for the development of graphene photodetectors. I will also present our recent results on exciting and detecting 1-ps-long graphene plasmon wavepackets.

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