



Château d'Orsay

WORKSHOP

Charge and heat dynamics in nano-systems

October 10-12, 2011, LPS Orsay

◆ ORGANIZING COMMITTEE

C. BENA - LPS Orsay
A. CRÉPIEUX - CPT Marseille

◆ SCIENTIFIC COMMITTEE

M. GOFFMAN - CEA Saclay
F. HEKKING - LPMCM Grenoble
F. MICHELINI - IM2NP Marseille
I. SAFI - LPS Orsay

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PEPS Physique Théorique et ses Interfaces, CNRS

PROGRAM

SESSION 1: DYNAMICS AND NOISE IN NANO-SYSTEMS I

October, Monday the 10th - Chairman: I. SAFI

- 14h C. GLATTLI Photon assisted shot noise and current
14h30 E. SUKHORUKOV Energy relaxation at the quantum Hall edge
15h P. DEGIOVANNI Quantum tomography of single electron excitations in quantum Hall edge channels
15h30 *Coffee break + Poster session*
16h30 M. BUTTIKER Distributions of waiting times of dynamic single-electron emitters
17h E. BOCQUILLON Intensity correlations of a single electron beam
17h30 T. JONCKHEERE Effect of many-body correlations on mesoscopic charge relaxation

SESSION 2: ONE-DIMENSIONAL SYSTEMS

October, Tuesday the 11th - Chairman: F. HEKKING

- 9h P. JOYEZ Andreev bound states and the Kondo effect in carbon nanotubes
9h30 A. LEVY YEYATI Cooper pair splitting based on carbon nanotubes
10h R. LOPEZ Josephson current in carbon nanotubes with spin orbit interaction
10h30 *Coffee break*
11h H. PERRIN Confining ultracold atoms on a ring in reduced dimensions
11h30 A. MINGUZZI Strongly interacting ultracold atomic gases on a 1D ring
12h J.-S. CAUX 1D quantum dynamics beyond the low-energy approximation

SESSION 3: DYNAMICS AND NOISE IN NANO-SYSTEMS II

October, Tuesday the 11th – Chairman: M. GOFFMAN

- 14h K. LE HUR Fluctuations and full counting statistics as probe of entanglement entropy
14h30 R. DEBLOCK Quantum noise measurement of a carbon nanotube quantum dot in the Kondo regime
15h P. SIMON Non-equilibrium frequency-dependent noise through a quantum dot:
A real time functional renormalization group approach
15h30 M. FERRIER Probing the dynamics of Andreev states in a coherent Normal/Superconducting ring
16h *Coffee break + Poster session*
17h A. ZAIKIN Shot noise and Coulomb effects on non-local electron transport in NSN heterstructure
17h30 F. PIERRE Strong back-action of a linear circuit on a single electronic quantum channel
18h F. PORTIER The bright side of Coulomb blockade

SESSION 4: HEAT TRANSFER AT THE NANOSCALE

October, Wednesday the 12th – Chairman: F. MICHELINI

- 9h A. BIEHS Radiative heat transfer at the nanoscale
9h30 D. NOZAKI Engineering the figure of merit and thermopower in single-molecule devices
connected to semiconducting electrodes
10h M. MUNZENBERG Magneto-Seebeck effect in magnetic tunnel junctions
10h30 *Coffee break*
11h L. PASCAL Circuit approach to photonic heat transport
11h30 J.-T. LU Heat transfer in molecular conductors due to Joule heating and current-induced force
12h S. MERABIA Thermal transport of molecular junctions

TALKS

Radiative heat transfer at the nanoscale

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3) Laboratoire Charles Fabry de l'Institut d'Optique, Université Paris-Sud, Palaiseau, France

We give a concise introduction into the radiative heat transfer at the nanoscale discussing the contribution of propagating, frustrated and coupled surface modes [1]. Especially, the latter contribution results in a heat flux, which can exceed the heat flux between two black bodies by several orders of magnitude for distances in the nanometer regime [1]. The prediction of such an enormous heat flux enhancement is usually based on Rylov's fluctuational electrodynamics [2] and has been verified in some very recent experiments [3,4,5]. Our aim is to show how the theoretical expression describing the nanoscale heat flux can be interpreted in terms of transmission coefficients and the universal quantum of thermal conductance by means of concepts of mesoscopic physics [6]. Such a formulation allows for studying the fundamental limits of radiative heat transfer [7,8] emphasizing the trade-off between the number of contributing modes and their transmission coefficient.

[1] K. Joulain, J.-P. Mulet, F. Marquier, R. Carminati, and J.-J. Greffet, *Surface Science Reports* 57, 59 (2005).

[2] S. M. Rylov, Y. A. Kravtsov, and V. I. Tatarskii, *Principles of Statistical Radiophysics* (Springer, New York), Vol. 3. (1989).

[3] S. Shen, A. Narayanaswamy, and G. Chen, *Nano Lett.* 9, 2909 (2009).

[4] E. Rousseau, A. Siria, G. Jourdan, S. Volz, F. Comin, J. Chevrier, and J.-J. Greffet, *Nature Photonics* 3, 514 (2009).

[5] R. Ottens, V. Quetschke, S. Wise, A. Alemi, R. Lundock, G. Mueller, D. H. Reitze, D. B. Tanner, B. F. Whiting, *Phys. Rev. Lett.* 107, 014301 (2011).

[6] S.-A. Biehs, E. Rousseau, and J.-J. Greffet, *Phys. Rev. Lett.* 105, 234301 (2010).

[7] P. Ben-Abdallah and K. Joulain, *Phys. Rev. B* 82, 121419 (R) (2010).

[8] S. Basu and Z. M. Zhang, *J. Appl. Phys.* 105, 093535 (2009).

Intensity correlations of a single electron beam

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The ballistic propagation of electronic waves in the quantum Hall edge channels of a 2DEG bears strong analogies with photon optics which inspired a whole set of experiments, including electronic Mach-Zehnder interferometers [1,2] and Hanbury-Brown and Twiss experiments with continuous sources [3,4]. However, the presence of the environment (thermal excitations, other edge channels) tends to invalidate a simple single particle picture. The injection and study of a few quasiparticles, emitted by a single electron source [5], gives a good tool to probe the propagation of a single particle in a complex environment. We report on the use of intensity correlations to characterize more accurately the properties of the emitted particles, in two different geometries. In the first experiment, short-time autocorrelations (high-frequency noise [6]) give access to the statistics of the emitted charges. Two theoretical models (based on heuristics [7] and on Floquet scattering theory) are confronted with the experimental results, providing a deep understanding of the physics. Under appropriate operating conditions, no spurious charge is detected and the noise reduces to the fundamental uncertainty on the emission time, thus demonstrating that single charge emission is achieved [8]. In the second experiment, partition noise measured in the Hanbury-Brown and Twiss geometry unveils the effects of the Fermi sea. The random partitioning of the incoming particles yields the number of excitations created by the source. However, only particles emitted at high energy ($\epsilon \gg kT_e$) are randomly partitioned and efficiently counted whereas particles at low energy ($\epsilon \approx kT_e$) are undistinguishable from thermal excitations and no excess noise is thus generated. The manipulation of single particles thus requires a proper engineering of the wavepackets, so as to distinguish them from thermal excitations. By changing the type of driving excitation (square, sinus...), our noise measurements show that we can modify the energy distribution of the emitted wavepackets.

[1] Ji, Y., Chung, Y., Sprinzak, D., Heiblum, M., Mahalu, D., and Shtrikman, H. (2003). *Nature*, 422 (6930), 415-8.

[2] Rouleau, P., Portier, F., Roche, P., Cavanna, A., Faini, G., Gennser, U., and Mailly, D. (2008). *Phys. Rev. Lett.*, 100 (12).

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[4] Oliver, W., Kim, J., Liu, R., and Yamamoto, Y. (1999). *Science*, 284 (5412), 299-301.

[5] Fève G., Mahé A., Berroir J.-M., Kontos T., Plaçais B., Glatli D. C., Cavanna A., Etienne B. and Jin Y., 2007 *Science* 316 1169.

[6] Parmentier, F. D., Mahé, A., Denis, A., Berroir, J.-M., Glatli, D. C., Plaçais, B., and Fève, G. (2011), *The Review of scientific instruments*, 82(1), 013904.

[7] Albert, M., Flindt, C., and Büttiker, M. (2010), *Phys. Rev. B*, 82(4), 41407.

[8] Mahé A., Parmentier F. D., Bocquillon E., Berroir J.-M., Glatli D. C., Kontos T., Plaçais B., Fève G., Cavanna A., Jin Y., *Phys. Rev. B*, 82(20), 201309.

Distributions of Waiting Times of Dynamic Single-Electron Emitters

M. Büttiker, *University of Geneva, Switzerland*

A periodically driven quantum capacitor may function as an on-demand single-electron source as it has recently been demonstrated experimentally. To characterize the accuracy at which single electrons are emitted, the noise spectrum has been measured [1] and discussed analytically [2]. If the charge emission can be resolved on the single particle level then we demonstrate that the fundamental quantity to be considered is the distribution of waiting times between subsequent emission events [3]. The waiting time distribution describes short-time physics and at the same time allows construction of the full counting statistics [3].

[1] A. Mahé, F. D. Parmentier, E. Bocquillon, J.-M. Berroir, D. C. Glatli, T. Kontos, B. Plaçais, G. Fève, A. Cavanna, and Y. Jin, *Phys. Rev. B* 82, 201309 (2010).

[2] M. Albert, C. Flindt, and M. Büttiker, *Phys. Rev. B* 82, 041407 (2010).

[3] M. Albert, C. Flindt, and M. Büttiker, *Phys. Rev. Lett.* 107, 086805 (2011).

1D quantum dynamics beyond the low-energy approximation

J.-S. Caux, *Instituut voor Theoretische Fysica, Amsterdam, Nederland*

The use of integrability for the calculation of correlation functions of one-dimensional quantum systems has yielded many results over the last few years. In this talk, after a very brief review, we will show how the non-universal prefactors of field theoretical expressions for correlation functions in one-dimensional quantum liquids can be obtained from a knowledge of the finite-size scaling of the exact state energies and operator matrix elements of the underlying integrable model. We will also discuss the extension of these methods and results beyond the low-energy limit.

Quantum noise measurement of a carbon nanotube quantum dot in the Kondo regime

J. Basset, A.Yu. Kasumov, C.P. Moca, G. Zarand, P. Simon, H. Bouchiat, and R. Deblock, *Laboratoire de Physique des Solides, Orsay, France*

The current emission noise of a carbon nanotube quantum dot in the Kondo regime is measured at frequencies ν of the order or higher than the frequency associated with the Kondo effect: the Kondo temperature T_K . The carbon nanotube is coupled via an on-chip resonant circuit to a quantum noise detector, a superconductor-insulator-superconductor junction. We find for $h\nu \approx k_B T_K$ a Kondo effect related singularity at a voltage bias $eV \approx h\nu$, and a strong reduction of it for $h\nu \approx 3 k_B T_K$, in good agreement with theory. Our experiment constitutes a new original tool for the investigation of the non-equilibrium dynamics of many-body phenomena in nanodevices.

Quantum tomography of single electron excitations in quantum Hall edge channels

P. Degiovanni, *Laboratoire de Physique, ENS Lyon, France*

The recent demonstration of an on demand single electron source [1,2] has opened the way to a new generation of "electron quantum optics" experiments aimed at preparing, manipulating and measuring coherent single electron excitations propagating in ballistic conductors such as the edge channels of a 2DEG in the integer quantum Hall regime. In this talk, I will describe a proposal [3] for measuring single electron coherence using an Hanbury Brown and Twiss interferometer. This quantum tomography protocol could be used to characterize single electron sources and to perform quantitative studies of decoherence.

[1] Science 316, 1169 (2007).

[2] Phys. Rev. B 82, 201309 (2010).

[3] New Journal of Physics 13, 093007 (2011).

Probing the dynamics of Andreev states in a coherent Normal/Superconducting ring

M. Ferrier, *Laboratoire de Physique des Solides, Orsay, France*

A dissipationless current is known to flow through a thin (subnanometer) insulating barrier between two superconductors S with a superconducting phase difference, the well-known Josephson effect. This supercurrent may also flow through a long (micrometer) non-superconducting metal wire at low temperatures, a spectacular consequence of the quantum phase coherence throughout the normal metal. The way the supercurrent responds to a dc phase difference, the current-phase relation [1], was only recently measured with a Hall probe [2]. It reflects the phase dependence of the Andreev bound states (ABS) [3], entangled electron-hole states which form in the normal metal as a consequence of the superconducting mirror-like boundary conditions. These phase dependent ABS were recently detected in a carbon nanotube between S electrodes. However little is known about the dynamics of ABS and their relaxation. In order to investigate the evolution of the current phase relation in such superconductor/normal metal/superconductor (SNS) junctions with high frequency phase driving, we have inductively coupled one NS ring to a multimode superconducting resonator. The in-phase (c') and out-of-phase (c'') ac magnetic susceptibility of the ring is deduced from the dc flux dependence of the resonance frequency and quality factor of the resonances from 300 MHz up to 6 GHz. Whereas at very low temperatures we essentially measure the phase derivative of the supercurrent, at higher temperature we find a strong frequency dependence in the current response of the ring: the ABS do not follow adiabatically the phase modulation. Indeed, different behaviors are observed for frequencies below and above the inverse of the diffusion time through the normal wire. Moreover, when increasing the rf excitation amplitude beyond linear response the out of phase response exhibits a strong increase close to odd multiples of a half flux quantum corresponding to the closing of the induced minigap in the N wire. These results are compared to recent theoretical findings and stimulate future similar investigations on more exotic junctions. This experiment also illustrates a new tool to probe the fundamental time scales of phase coherent systems that are decoupled from macroscopic normal contacts and thermal baths.

[1] Heikkila, T. T. Sarkka, J. and Wilhelm, F. K., Phys. Rev. B 66, 184513 (2002).

[2] Fuechsle, M. et al., Phys. Rev. Lett. 102, 127001 (2009).

[3] Kulik, I., Sov. Phys. JETP 30, 944 (1970).

Photon assisted shot noise and current

C. Glattli, *Nanoelectronics group, SPEC CEA Saclay Gif-sur-Yvette, also at Mesoscopic Physics Group, LPA ENS Paris, France*

We review some physical aspects of shot noise of quantum conductors with no dc voltage bias applied but submitted to high frequency voltage fluctuations. The resulting generation of neutral electron-hole pair excitations by photon absorption can be detected as a current when the electronic mode transmission is energy dependent. This photocurrent response to the external radiation depends on specific characteristic energies and is sensitive but non universal. The photon assisted shot noise PASN however is a direct measure of the number of electron-hole pairs and is observable even for energy independent transmissions. PASN simply originates from electron and holes separately partitioned by elastic scattering in the conductor. PASN does not require energy dependence of the transmissions. Counting electron-hole pairs via shot noise finds fundamental applications such as characterising the quality of few electron sources, or applications such as photo-detection. After recalling the known results when the voltage fluctuations arise from a monochromatic photon source, we will focus on the case of a classical white noise

source such as a hot resistor for both PASN and photon assisted current where the energy density of electron-hole pairs is given by the $P(E)$ probability. Finally we will discuss some photon statistics effects on current correlations.

Many-body correlation effect on mesoscopic charge relaxation

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We investigate non-perturbatively the charge relaxation resistance and quantum capacitance in a coherent RC circuit in the strong-coupling regime. We find that the many-body correlations break the universality in the charge relaxation resistance: (i) The charge relaxation resistance has peaks at finite frequencies given by the effective level broadening, and (ii) the zero-frequency resistance deviates from the universal value when the Zeeman splitting is comparable to this level broadening. This behavior becomes even more prominent in the Kondo regime. The observed features are ascribed to the generation of particle-hole excitations in the contacts accomplished by spin-flip processes in the dot.

Andreev bound states and the Kondo effect in carbon nanotubes

P. Joyez, CEA Saclay, France

We have performed tunneling spectroscopy of carbon nanotubes well connected to aluminum contacts. I will show that the behavior of the devices is well described by a double quantum dot model with a significant hopping term between the two dots. The novelty of our spectroscopic measurements is that they reveal directly the internal DOS of these coupled quantum dots. In the experiment, two gates allow to tune the two dots independently. Depending on the gate voltages we can have the two dots behaving like independent artificial atoms or sharing electrons in "molecular state". In both "atomic" or "molecular" situations we observe a Kondo effect when the Al contacts are in the normal state, and Andreev Bound States when the contacts are superconducting. I will show that most single-dot ("atomic") features are well understood, and I will make the correspondence between the normal and the superconducting state measurements. As for the "molecular" features, the analysis is in progress.

Fluctuations and full counting statistics as probe of entanglement entropy

K. Le Hur, Department of Physics, Yale University, New Haven, USA

We introduce the concept of bipartite fluctuations of particle number in relation with many-body entanglement. We propose that the bipartite fluctuations are an effective tool for studying many-body quantum systems in the same way as noise and full counting statistics in mesoscopic transport and cold atomic gases. For systems that can be mapped to a problem of non-interacting fermions we show that the (bipartite) charge fluctuations and their generalized cumulants fully encode the information needed to determine the entanglement and Renyi entropy. To illustrate this idea, we consider a simple nano-entangler: the quantum point contact.

Cooper pair splitting based on carbon nanotubes

A. Levy Yeyati, Universidad Autónoma de Madrid, Spain

Recent experiments [1,2] have demonstrated that double quantum dots coupled to a superconducting lead are promising candidates for producing non-local spin-entangled electrons using a solid state device. After a brief introduction to the subject I shall present an analysis of the experimental results of Herrmann et al. [2] based on a phenomenological model. In a second step I shall give a microscopic description of double dot formation in carbon nanotubes and the conditions to increase the splitting efficiency up to close 100% by working in the non-linear regime [3].

[1] L. Hofstetter et al. Nature 461, 960 (2009).

[2] L.G. Herrmann et al. Phys. Rev. Lett. 104, 026801 (2010).

[3] P. Bursset, W. Herrera and A. Levy Yeyati, Phys. Rev. B (to be published).

Josephson current in carbon nanotubes with spin orbit interaction

R. Lopez, Institut de Física Interdisciplinar i Sistemes Complexos, Palma de Mallorca, Spain

We demonstrate that curvature-induced spin-orbit (SO) coupling induces a $0-\pi$ transition in the Josephson current through a carbon nanotube quantum dot coupled to superconducting leads. In the non-interacting regime, the transition can be tuned by applying parallel magnetic field near the critical field where orbital states become degenerate. Moreover, the interplay between charging and SO effects in the Coulomb Blockade and cotunneling regimes leads to a rich phase diagram with well-defined (analytical) boundaries in parameter space. Finally, the 0 phase always prevails in the Kondo regime. Our calculations are relevant in view of recent experimental advances in transport through ultra-clean carbon nanotubes.

Heat transfer in molecular conductors due to Joule heating and current-induced force

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1) DTU Nanotech, Department of Micro and Nanotechnology, NanoDTU, Technical University of Denmark

2) Niels Bohr Institute, Nano-Science Center, University of Copenhagen, Denmark

We derive a semi-classical Langevin equation to describe the ion dynamics of a molecular conductor in the presence of electrical current. The classical ions, like Brownian particles, feel the friction and fluctuating force from their quantum electronic [1] and phononic environment [2].

Some known results are recovered from the Langevin equation: (1) the Joule heating result agrees with that from fully quantum mechanical nonequilibrium Green's function approach [3], (2) a non-conservative part and an effective magnetic part of the current-induced force are identified, as discussed recently [4,5,6]. We use this approach to study the heat transfer from the electrons to the molecular vibrations, and from the vibrations to the electrode phonon baths. The effect of the new forces on heat transfer is highlighted.

- [1] M. Brandbyge, and P. Hedegård, *Phys. Rev. Lett.*, 72, 2919 (1994).
- [2] J. S. Wang, *Phys. Rev. Lett.*, 99, 160601 (2007).
- [3] M. Paulsson, T. Frederiksen, and M. Brandbyge, 72, 201101(R), (2005).
- [4] D. Dundas, E. J. McEniry and T. N. Todorov, *Nature Nanotech.*, 4, 99 (2009).
- [5] J. T. Lü, M. Brandbyge, and P. Hedegård, *Nano Letters*, 10, 1657 (2010).
- [6] J. T. Lü, P. Hedegård, and M. Brandbyge, *Phys. Rev. Lett.*, 107, 046801 (2011).

Thermal transport of molecular junctions

S. Merabia, *Laboratoire de Physique de la Matière Condensée et Nanostructures, Lyon, France*

I will discuss some aspects of heat transfer around heated nanoparticles suspended in a solid or liquid matrix. This situation, which is relevant to ultrafast pump-probe spectroscopy experiments, raises new questions regarding heat transfer at the nano-scale: How is heat transfer limited by the interfacial thermal resistance of the nanoparticle/matrix? Can heat transfer induce phase change of the surrounding medium? How energy can be transferred between nanoparticles? I will discuss and interpret theoretically recent experiments probing the cooling kinetics of metal particles embedded in a glassy matrix. I will show how the thermal resistance depends on the acoustic impedance mismatch at the glass/metal interface. Then, I will present simulation results of an ideal molecular junction connecting two nanoparticles. In this latter example, I will discuss the effect of the solvent on the conductance of the junction.

Strongly interacting ultracold atomic gases on a one-dimensional ring

A. Minguzzi, C. Schenke, and F.W.J. Hekking,

Universite Grenoble 1 and CNRS, Laboratoire de Physique et Modélisation des Milieux Condensés, Grenoble, France

Ultracold atoms are novel quantum fluids which allow for unprecedented tunability of the system parameters, as both the interaction strength and the geometry can be adjusted. Recent experimental advances have demonstrated the possibility of trapping ultracold atoms on a ring, as well as the possibility to stirring them by setting into motion a barrier potential along the trap circumference. We consider a strongly interacting quasi-one dimensional Bose gas on a tight ring trap subjected to a localized barrier potential which is suddenly set into motion. In the impenetrable boson (Tonks-Girardeau) limit we find an exact solution for the quantum dynamics of the system. Evaluation of the particle current and of the drag force acting on the barrier allows to study the superfluid-like behaviour of the gas. By accurately tuning the barrier velocity, we also show that it is possible to generate robust macroscopic superpositions of current states.

Magneto-Seebeck effect in magnetic tunnel junctions

M. Munzenberg, *Goerg-August-Universität Göttingen, 37077 Göttingen, Germany*

Creating temperature gradients in magnetic nanostructures has resulted in a new research direction, i.e., the combination of magneto- and thermoelectric effects. Nanoscale magnetic tunnel devices, known for application as magnetic sensor in hard disc drives or magnetic random access memories (MRAM), show large magnetoresistance. By the application of laser heating using a small focus, a Seebeck voltage is generated by this thermal heat gradient at the tunnel barrier. It can be controlled via the magnetization. The Seebeck coefficient changes during the transition from a parallel to an antiparallel magnetic configuration in a tunnel junction – the magneto-Seebeck effect. In that respect, it is the analog to the tunneling magnetoresistance. The Seebeck coefficients in parallel and antiparallel configuration are in the order of the voltages known from the charge-Seebeck effect. However here the geometric center of the electronic density of states relative to the Fermi level determines the size of the magneto-Seebeck effect. Generally strong electronic asymmetry at around the Fermi level results in a strong Seebeck effect. The size and sign of the effect can be controlled by the composition of the electrodes' atomic layers adjacent to the barrier and the temperature. The magnetization dependence originates from the switching of the thermal spin transmission that give rise to Seebeck coefficients in the parallel and the antiparallel case varying up to >100% and in sign. The large effect originates from the half metallic behavior of the tunnel junction. I will present the first experimental verification of this novel effect experimentally.

- [1] M. Walter, J. Walowski, V. Zbarsky, M. Münzenberg, M. Schäfers, D. Ebke, G. Reiss, A. Thomas, P. Peretzki, M. Seibt, J.S. Moodera, M. Czerner, M. Bachmann, and C. Heiliger, *Nature Materials*, advance online (2011).
- [2] M. Czerner, M. Bachmann, and C. Heiliger, *Phys. Rev. B* 83, 132405 (2011).

Engineering the figure of merit and thermopower in single-molecule devices connected to semiconducting electrodes

D. Nozaki, *Institute for Materials Science, Dresden, Germany*

The versatility of nanostructures opens opportunities to create new types of molecular devices. The controlling of their electronic structure and thermal transport enables an efficient thermoelectric conversion [1-3]. In this study, we propose a possible route to achieve high thermoelectric efficiency in molecular junctions by combining (1) a local chemical tuning of the molecular electronic states and (2) the use of semiconducting electrodes [4]. The former allows for the control of the position of the highest-occupied molecular orbital (HOMO) transmission resonance with respect to the Fermi energy, while the latter fulfils a twofold purpose: the suppression of electron-like contributions to the thermopower, and the cutting-off of the HOMO transmission tails into the semiconductor band gap. After proving this principle with a toy model, we demonstrate that a large thermopower can be obtained within density-functional tight-binding theory [5]. Our results strongly suggest that large figures of merit can be achieved in such molecular junctions.

- [1] P. Reddy, S.-Y. Jang, R. A. Segalman, and A. Majumdar, *Science* 315, 1568 (2007).
- [2] T. T. M. Vo, A. J. Williamson, V. Lordi, and G. Galli, *Nano Lett.* 8, 1111 (2008).
- [3] A. Boukai, Y. Bunimovich, J. Taher-Kheli, J. K. Yu, W. Goddard III, and J. R. Heath, *Nature*, 451, 168 (2008).

[4] D. Nozaki, H. Sevinçli, W. Li, R. Gutiérrez, and G. Cuniberti, Phys. Rev. B 81, 235406 (2010).

[5] <http://www.dftb.org> and <http://www.dftb-plus.info>

Circuit approach to photonic heat transport

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We discuss the heat transfer by photons between two metals coupled by a circuit containing linear reactive impedances. Using a simple circuit approach, we calculate the spectral power transmitted from one metal to the other and find that it is determined by a photon transmission coefficient which depends on the impedances of the metals and of the coupling circuit. We study the total photonic power flow for different coupling impedances both in the linear regime where the temperature difference between the metals is small and in the nonlinear regime of large temperature differences. These results [1] justify that we neglect the photons heat contribution in our experiment investigating the different thermal phenomena taking place in superconducting hybrid nanostructures [2]. We experiment by using Normal-Insulator-Superconductor junctions as heating or cooling sources and as thermometers. The device allows to measure independently the temperature of electron and phonon populations. This enables us to quantify the various thermal couplings (electron-phonon coupling and Kapitza coupling) involved in mesoscopic devices.

[1] L.M.A. Pascal et al, Phys. Rev. B 83, 125113 (2011).

[2] S. Rajauria et al, Phys. Rev. Lett. 99, 047004 (2007).

Confining ultracold atoms on a ring in reduced dimensions

H. Perrin, Laboratoire de Physique des Lasers, Paris Villetaneuse, France

Ultra cold atoms are a wonderful tool for the study of quantum matter. They can be manipulated by light of magnetic fields, trapped to reduced dimensions either in harmonic traps or in more arbitrary geometry, and easily detected by interaction with resonant light. Bosons or fermions can be cooled to low temperatures to produce degenerate samples, superfluid bosons in Bose-Einstein condensates or fermions in the BCS regime. Analogies with condensed matter systems are numerous, including the Mott insulator to superfluid transition, Anderson localisation and the possibility of an atomic SQUID. In this talk, I will focus on the way of preparing atoms in low dimensions, either in 1D or 2D layers, in linear/planar or ring geometry. I will give the state of current experiments, including our last experimental results toward the production of a degenerate sample in a ring trap. Both the adjustable parameters and the diagnostic tools will be discussed.

Strong back-action of a linear circuit on a single electronic quantum channel

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The question of which laws govern electricity in mesoscopic circuits is a fundamental matter that also has direct implications for the quantum engineering of nanoelectronic devices. When a quantum-coherent conductor is inserted into a circuit, its transport properties are modified. First, electronic quantum interferences blend the conductor with its vicinity, resulting in a different coherent conductor. Furthermore, the circuit back-action modifies the full counting statistics of charge transfers across coherent conductors; in particular, their conductance is reduced. This so-called environmental Coulomb blockade, which is our concern here, therefore results in violations of the classical impedance composition laws even for distinct circuit elements, separated by more than the electronic phase coherence length. The circuit back-action originates from the granularity in the transfer of charges across a coherent conductor. As a result of Coulomb interactions, an excitation by these current pulses of the circuit electromagnetic modes is possible, which impedes the charge transfers. Although extensively studied for a tunnel junction in a linear circuit, it is only fully understood for arbitrary short coherent conductors in the limit of small circuit impedances and small conductance reduction. The present work investigates experimentally the strong-back-action regime, with a conductance reduction of up to 90%. This is achieved by embedding a single quantum channel of tunable transmission in an adjustable on-chip circuit of impedance comparable to the resistance quantum h/e^2 at microwave frequencies. The experiment reveals significant deviations from calculations performed in the weak back-action framework, and matches with recent theoretical results. Based on these measurements, we propose a generalized expression for the conductance of an arbitrary quantum channel embedded in a linear circuit.

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The Bright side of Coulomb blockade

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The electromagnetic environment of a tunnel junction can modify the current through the junction because the sudden charge transfer associated with a tunnel event can generate photons in the environment. This dissipation process, called dynamical Coulomb blockade (DCB), tends to reduce the current through a normal metal junction at low bias and in the case of a Josephson junction allows for a Cooper pair current at non-zero bias voltage [1]. DCB has been extensively studied and is well understood [2], yet the radiation emitted into the electromagnetic environment has never been observed. With the advent of circuit quantum electrodynamics, the quantum properties of the photons emitted could now become useful. We explore this bright (photonic) side of DCB by measuring the radiation emitted by a voltage-biased Josephson junction embedded in a microwave resonator. We have measured simultaneously the Cooper pair current and the photon emission rate at the resonance frequency of the resonator. Our results show two regimes in which each tunneling Cooper pair emits either one or two photons into the resonator. The spectral properties of the emitted radiation are accounted for by an extension to DCB theory.

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[2] H. Grabert and M. H. Devoret (editors). Single charge tunneling. Plenum Press (1992). In particular chapter 2 by G.-L. Ingold and Y. V. Nazarov.

Non-equilibrium frequency-dependent noise through a quantum dot: A real time functional renormalization group approach

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Probing the fast dynamics of many-body correlated systems has been the subject of longstanding research activity. Due to recent progress in nanotechnology, it is now feasible to design nanoscale devices in which correlated effects appear under out of equilibrium conditions. The Kondo effect in quantum dots constitutes in this respect a paradigmatic model system, where a single electron spin of the quantum dot is dynamically screened by the conduction electrons below a characteristic energy scale, the Kondo temperature T_K . In order to study frequency-dependent transport and noise through a quantum dot in the local moment regime, we construct a real time current-conserving functional renormalization group (RG) scheme on the Keldysh contour. We find that the current vertex develops a non-trivial non-local structure in time, governed by a new set of RG equations. Solving these RG equations, we compute the complete frequency and temperature-dependence of the noise spectrum. For voltages large compared to the Kondo temperature, $eV \gg k_B T_K$, two sharp anti-resonances are found in the noise spectrum at frequencies $\hbar\omega = \pm eV$, and correspondingly, two peaks in the ac conductance through the dot [1]. These theoretical predictions will be compared to recent experimental results on high frequency noise measurements of a carbon nanotube quantum dot in the Kondo regime [2].

[1] C. P. Moca, P. Simon, C.-H. Chung, and G. Zarand, *Phys. Rev. B* 83, 201303(R) (2011).

[2] J. Basset, A. Yu. Kasumov, C. P. Moca, G. Zarand, P. Simon, H. Bouchiat, and R. Deblock, submitted.

Energy relaxation at the quantum Hall edge

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In this work we address recent experiment of Altimiras and collaborators [*Nature Physics* 6, 34 (2010)], where an electron distribution function at the quantum Hall (QH) edge at filling factor 2 has been measured with high precision. It has been reported that the energy of electrons injected into one of the two chiral edge channels with the help of a quantum point contact (QPC) is equally distributed between them, in agreement with earlier predictions, one being based on the Fermi gas approach, and the other utilizing the Luttinger liquid theory. We argue that the physics of the energy relaxation process at the QH edge may in fact be more rich, providing the possibility for discriminating between two physical pictures in experiment. Namely, using the recently proposed non-equilibrium bosonization technique [*PRL* 103, 036801 (2009)] we evaluate the electron distribution function and find that the initial "double-step" distribution created at a QPC evolves through several intermediate asymptotics, before reaching eventual equilibrium state. At short distances the distribution function is found to be strongly asymmetric due to non-Gaussian current noise effects. At larger distances, where noise becomes Gaussian, the distribution function acquires symmetric Lorentzian shape. Importantly, in the regime of low QPC transparencies, $T \ll 1$, the width of the Lorentzian scales linearly with T , in striking difference with the equilibrium Fermi distribution, whose width scales as square root of T . Therefore, we propose to do measurements at low QPC transparencies.

Shot noise and Coulomb effects on non-local electron transport in NSN heterstructures

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We demonstrate a close relation between Coulomb effects in non-local electron transport and non-local shot noise in three-terminal metallic conductors. Provided the whole structure is normal, cross-correlations in shot noise are negative and Coulomb interaction tends to suppress both local and non-local conductances of the system. The behavior of normal-superconducting-normal structures at subgap energies is entirely different. In the tunneling limit non-local differential conductance of such systems is found to have an S-like shape and it can turn negative at non-zero bias. At high transmissions crossed Andreev reflection yields positive noise cross-correlations and Coulomb anti-blockade of non-local electron transport.

POSTERS

Current and noise correlations in a double-dot Cooper-pair beam splitter

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We consider a double quantum dot coupled to two normal leads and one superconducting lead, modelling the Cooper pair beam splitter studied in two recent experiments. Starting from a microscopic Hamiltonian we derive a general expression for the branching current and the noise crossed correlations in terms of a single- and two-particle Green's function of the dot electrons. We then study numerically how these quantities depend on the energy configuration of the dots and the presence of direct tunnelling between them, isolating the various processes which come into play. In the absence of direct tunneling, the antisymmetric case (the two levels have opposite energies with respect to the superconducting chemical potential) optimizes the crossed Andreev reflection (CAR) process while the symmetric case (the two levels have the same energies) favours the elastic cotunneling (EC) process. Switching on the direct tunneling tends to suppress the CAR process, leading to negative noise crossed correlations over the whole voltage range for large enough direct tunneling.

Josephson junctions with long range interactions, phase slip proliferation versus Kosterlitz-Thouless transition

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One-dimensional superconducting wires may cease to be superconducting at very low temperature due to the proliferation of quantum phase slips. This problem is analogous to Josephson junction chains with a poorly screened long range part of the Coulomb interaction, which alters the Kosterlitz-Thouless transition. I-V curves are calculated, this can also be relevant for Andreev reflection in fabricated Josephson junction chains.

Quartet correlations between Cooper pairs in a mesoscopic double Josephson junction

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Two Josephson junctions separated by less than the superconducting coherence length involve higher order processes, that can be quite sizeable for more transparent junctions. Those processes originate from crossed Andreev reflections (CAR), where Cooper pairs are split into two spin-entangled electrons. In an $S_a - S - S_b$ bijunction, double CAR simultaneously produces two Cooper pairs, one in each junction. This amounts to produce nonlocal quartets in the superconductors S_a and S_b [1]. Cooper pairs being pseudo-bosons, this mechanism bears some similarity with the emission of pairs of time-correlated photons in Quantum Optics, thus the name "superconducting beam splitter" given to the basic bijunction set-up. Energy conservation implies that a coherent dc quartet current can flow even if S_a and S_b are biased at respective voltages V and $-V$, thus offering the possibility of dc Josephson effect in biased junction arrays. We will review several consequences and possible detection of quartet currents. They rely on a superconducting circuit having 3 (and not 2) current terminals. Dc quartet current can be detected by the synchronization of the ac Josephson oscillations in each contact a and b, either with $V_a = V$ and $V_b = -V$, or adding a small dc and ac components such as to achieve Shapiro steps for quartet motion. The potential of quartet production in superconducting circuits includes entanglement, that can be continuously controlled by a superconducting phase.

[1] A. Freyn, B. Douçot, D. Feinberg, and R. Mélin, Phys. Rev. Lett. 106, 257005 (2011).

Giant charge relaxation resistance in the Anderson model

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We study the dynamical conduction properties of a metallic lead connected to a quantum dot viewed as an Anderson impurity and where a gate voltage induces the AC regime. Under a strong magnetic field, the edge-states of a 2d electron gas exchange electrons with the impurity by tunnel effect. This system can be seen as a quantum RC circuit. We show that a generalized Korrington-Shiba relation can be derived by applying low-energy effective Fermi liquid theory at zero temperature. This gives access to the charge-relaxation resistance which is expressed in terms of static susceptibilities which are analytically obtained by the Bethe Ansatz. We show that this resistance strongly depends on the magnetic field, showing a pronounced peak caused by the destruction of the Kondo singlet by the Zeeman effect, which disappears at the particle-hole symmetric point.

Widely tunable phase-preserving Josephson amplifier near the quantum limit

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We present the first experimental realization of a widely tunable and non-degenerate Josephson Parametric Amplifier. For this purpose, we developed a new superconducting building-block based on a ring of four Josephson junctions shunted by a cross of four linear inductances. As the inductance of the ring depends strongly on flux bias, the frequency of the resonators can be tuned over more than 400 MHz. Finally, we illustrate the usefulness of the amplifier by measuring the noise spectrum emitted by a voltage biased tunnel junction at finite frequency. We are able to resolve the crossover between zero-point-fluctuations and shot noise with unprecedented accuracy.

Spin Hall effect at interfaces between HgTe/CdTe quantum wells and metals

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On this poster, we first show the existence of a new type of spin Hall effect at the interface between HgTe/CdTe quantum wells and metals (normal and superconducting ones). The new type of SHE is intimately related to the coexistence of propagating and evanescent modes at the interface. Interestingly, this happens in the absence of structure and bulk inversion asymmetry within each subsystem. Then, we functionalize these findings to propose a device for all-electric spin injection into normal metal leads [Gui11].

[Gui11] M. Guigou, P. Recher, B. Trauzettel, and J. Cayssol, arXiv:1102.5066 (accepted in PRB).

Coupling a quantum dot, fermionic leads and a microwave cavity on-chip

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We demonstrate a hybrid architecture consisting of a quantum dot circuit coupled to a single mode of the electromagnetic field. We use single wall carbon nanotube based circuits inserted in superconducting microwave cavities. By probing the nanotube-dot using a dispersive read-out in the Coulomb blockade and the Kondo regime, we determine an electron-photon coupling strength which should enable circuit QED experiments with more complex quantum dot circuits.

Adiabatic transport in the interacting resonant level model

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We develop a generic method in Liouville space to describe the dissipative dynamics of coherent interacting quantum dots with adiabatic time dependence. We apply the method to the interacting resonant level model and calculate the adiabatic response to time-dependent gate voltages, tunnelling barriers and Coulomb interaction. Besides universal charge relaxation resistance we find logarithmic corrections and discuss the observability in molecular systems and cold atom setups.

Spin-dependent density of states and currents in a multiterminal ferromagnet-superconductor heterostructure

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To describe the spin-dependent transport properties of diffusive heterostructures containing superconducting and ferromagnetic elements quasiclassical Green's functions are a powerful tool. Here we present a correction to the boundary conditions for diffusive systems introduced in Phys. Rev. B 80, 184511 (2009) for the case of weakly polarized tunnel interfaces. The interface properties are described by a few parameters containing the spin-dependent interfacial phase shifts and spin-filtering effects. We apply our theory to a three terminal proximity system consisting of two noncollinear ferromagnetic and a superconducting terminal coupled via tunneling barriers. We discuss the density of states and its projections on different magnetization directions to understand the local and nonlocal spin-dependent currents.

Spin-Hall conductance fluctuations in magnetic disordered systems

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In two dimensional electron systems with randomly distributed magnetic impurities large fluctuations of the dynamical spin conductivity are observed, mainly at low frequencies. This explains the large dispersion of the static spin Hall conductivity around its mean value. I will investigate the universality of those fluctuations and discuss its influence on spin transport.

Macroscopic superpositions by nonadiabatic stirring of a Tonks-Girardeau gas on a 1D ring

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We consider a strongly interacting quasi-one dimensional Bose gas on a tight ring trap subjected to a localized barrier potential which is suddenly set into motion. Using an exact solution for the dynamical evolution in the impenetrable-boson (Tonks-Girardeau) limit, we predict the formation of a macroscopic superposition of a rotating and a nonrotating state. We find that the barrier velocity should be tuned close to multiples of integer or half-integer number of Coriolis flux quanta to maximize the nonadiabatic excitation, and it should be larger than the sound velocity to better discriminate the two components of the superposition

Poissonian tunneling through an extended impurity in the quantum Hall effect

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We consider transport in the Poissonian regime between edge states in the quantum Hall effect. The backscattering potential is assumed to be arbitrary, as it allows for multiple tunneling paths. We show that the Schottky relation between the backscattering current and noise can be established in full generality: the Fano factor corresponds to the electron charge (the quasiparticle charge) in the integer (fractional) quantum Hall effect, as in the case of purely local tunneling. We derive an analytical expression for the backscattering current, which can be written as that of a local tunneling current, albeit with a renormalized tunneling amplitude which depends on the voltage bias. We apply our results to a separable tunneling amplitude which can represent an extended point contact in the integer or in the fractional quantum Hall effect. We show that the differential conductance of an extended quantum point contact is suppressed by the interference between tunneling paths, and it has an anomalous dependence with respect to the bias voltage.

Coherent thermoelectric effects in mesoscopic Andreev interferometers

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We investigate thermoelectric transport through Andreev interferometers. We show that the ratio of the thermal and the charge conductance exhibits large oscillations with the phase difference, ϕ , between the two superconducting contacts, and that the Wiedemann-Franz law holds only when $\phi = \pi$. A large average thermopower furthermore emerges whenever there is an asymmetry in the dwell times to reach the superconducting contacts. When this is the case, the thermopower is odd in ϕ . In contrast, when the average times to reach either superconducting contact are the same, the average thermopower is zero, however mesoscopic effects (analogous to universal conductance fluctuations) lead to a sample-dependent thermopower which is systematically even in ϕ [Ph. Jacquod and R.S. Whitney, Europhys. Lett. 91, 67009 (2010)].

A one-channel conductor coupled to a quantum of resistance: exact ac conductance and finite-frequency noise

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We consider a one-channel coherent conductor with intermediate or good transmission embedded into an ohmic environment whose resistance is equal the quantum of resistance. Our choice is motivated by the mapping of this problem to a Tomonaga-Luttinger liquid whose interaction parameter corresponds to the specific value $K=1/2$ which allows a refermionization procedure. We compute, for the first time, the finite frequency conductance and the non-symmetrized finite-frequency noise. Surprisingly, both cannot be expressed within the scattering approach for the new fermions, even though they are still determined by the transmission functions. We also show that the emission excess noise vanishes exactly above eV, which is surprising as the underlying Tomonaga-Luttinger liquid model corresponds to a many-body correlated system. Our results apply for all ranges of temperature, voltages and frequencies below the RC frequency, and allow to explore fully the quantum regime.

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