Opportunities from Local Noise Spectroscopy Workshop

Leiden

November 20-24, 2023

Final Program

(last updated: November 8, 2023)

organized by Lorentz Center and DIPC

Opportunities from local noise spectroscopy

	Monday (20.11)	Tuesday (21.11)	Wednesday (22.11)	Thursday (23.11)
Morning 1	9:00 - 10:00 Registration and coffee 10:00 - 10:15 Welcome and brief introduction by the Lorentz Center	9:00 – 10:00 **Eugene Demler** Single-spin qubit magnetic spectroscopy of correlated states of electrons	9:00 – 10:00 **Wolfgang Belzig** Full Counting Statistics Probe of Local Correlations in Transport	9:00 – 10:00 **Katharina Franke** Josephson junctions with single magnetic adatoms
	10:15 – 10:30 Introduction of the goals of the workshop	10:00 – 10:30 Coffee break	10:00 – 10:30 Coffee break	10:00 – 10:30 Coffee break
Morning 2	10:30 – 11:30 **Yaroslav Blanter** Electron shot noise	10:30 - 11:30 **Thomas Frederiksen** Photon-emission statistics from biased single-molecule junctions	10:30 – 12:00 Poster session (premade posters) about recent results and theoretical ideas.	10:30 – 11:30 **Ludovico Tesser** How much noise is necessary in mesoscopic engines? 11:30 - 12:00 Special poster session: white board-posters about ideas.
Lunch	12:00 - 13:00 Adventures in Dutch cuisine	12:00 - 13:30 Adventures in Dutch cuisine	12:00 - 13:30 Adventures in Dutch cuisine	12:00 - 13:30 Adventures in Dutch cuisine
Afternoon 1	13:00 - 13:30 Ice-breaker event. Participants get to know each other. 13:30 – 14:30 **Jan van Ruitenbeek** A brief overview of experiments on noise 14:30 – 15:30 **Jianfeng Ge** Introduction to local noise spectroscopic experiments	13:30 – 14:30 **Dario Bercioux** Filling anomaly in obstructed atomic & fragile topological insulators 14:30 – 15:30 **Ingmar Swart** Fractional charges in atomically precise lattices	13:30 – 14:30 **Pascal Simon** New insights from electronic transport in superconducting bound-states 14:30 – 15:30 **Freek Massee** Tunnelling process into sub-gap states in NbSe2 revealed by atomic scale shot-noise	13:30 – 14:30 **Jon Ortuzar Andres** Magnetic impurities on superconducting proximitized metals 14:30 – 15:30 **Jiasen Niu** Why shot noise does not generally detect pairing in mesoscopic superconducting tunnel junctions
		15:30- 16:00 Coffee break	15:30- 16:00 Coffee break	15:30- 16:00 Coffee break
Afternoon 2	16:00 – 17:30 Welcoming event by the Lorentz Center	16:00 – 17:30 Moderated discussion about most promising avenues.	16:00 – 17:30 Moderated discussion about most promising avenues.	16:00 – 17:30 Moderated discussion: prospects and ideas. Setting agenda for further cooperation.
Evening		18:00 – 19:00 Bar bites in the city center	18:00 – 19:00 Conference dinner	

Venue and Contact Data

Organizers: Milan Allan, Anastasiia Skurativska, Dario Bercioux, Ingmar Swart

Workshop Coordinator: Marieke Brock

Contact: LocalNoiseSpectroscopy@lorentzcenter.nl

Website: www.lorentzcenter.nl

Venue: Lorentz Center@Snellius (Follow Google Maps)

Sponsors: The workshop is financially supported by DIPC and the Lorentz Center

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Abstracts

Talk: Electron shot noise

20 Nov
10:30
11:30

Yaroslav M. Blanter

Kavli Institute of Nanoscience, Delft University of Technology, Lorentzeg 1 2628 CJ, the Netherlands

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This will be mostly a tutorial on (mesoscopic) shot noise in electron transport, covering normal and hybrid normal-superconducting systems, as well as the full counting statistics in these systems. At the end of the talk, I will briefly present my recent research, concentrating on electron transport in cable bacteria.

Talk: A brief overview of experiments on noise

20 Nov
13:30
14:30

Jan van Ruitenbeek

Leiden University, Niels Bohrweg 2, Leiden 2333 CA, The Netherlands

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Although electronic shot noise had been identified and understood since the 1920's, it was only with the rise of mesoscopic physics and nanophysics that it came to be exploited for as a tool for investigating the fundamental properties of these systems. I will give a brief historical perspective on the key experimental techniques and discoveries, and indicate some promising further directions of experimental investigation.

Talk: Introduction to local noise spectroscopic experiments

20 Nov
14:30
15:40

Jianfeng Ge

Leiden University, Niels Bohrweg 2, Leiden 2333 CA, The Netherlands

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In this talk, I will show how we carry out our local noise spectroscopic experiments. I will focus on electronic design & its recent improvement, integration with standard scanning tunneling spectroscopy/microscopy, and noise imaging. I will show applications from our recent publications, and discuss on the abilities and limitations of state-of-the-art local noise measurements.

Talk: Single-spin qubit magnetic spectroscopy of correlated states of electrons

21 Nov
9:00
10:00

Eugene Demler

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A single-spin qubit placed near the surface of a material acquires an additional contribution to its relaxation rate due to magnetic noise created by the low-energy excitations of the electron system. I will discuss how this noise can be used to investigate different types of electronic states, including superconductors, ferro- and antiferromagnetic insulators, spin-liquid states, and one-dimensional systems.

Talk: Photon-emission statistics from biased single-molecule junctions

21 Nov
10:30
11:30

Thomas Frederiksen

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Recent experiments utilizing Scanning Tunneling Microscopy (STM) have shed light on the intriguing phenomena of single-molecule fluorescence, especially when induced by tunneling currents in nanoplasmonic cavities. These current fluctuations, reminiscent of shot noise, can result in photon excitations due to the electric field of the cavity mode interacting with the molecule's charge fluctuations. In this contribution, I will discuss our ongoing theoretical efforts to better comprehend such processes. Focusing on scenarios with a pronounced damping rate for the cavity mode, we explore insights into the relationships between electronic current, the second-order photon correlation function, and the electron-cavity coupling strength in simple models. While our investigations are still evolving, they aim to pave the way for a deeper understanding of the underlying mechanisms of light emission in biased single-molecule junctions.

Talk: Filling anomaly in obstructed atomic & fragile topological insulators

21 Nov
13:30
14:30

Dario Bercioux

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In this talk, I will revise the historical model by Jackiew & Rebbi for fermions in one dimension. I will move to the more realistic Su–Schrieffer–Heeger model for describing polyacetylene. In this contest, I will introduce the concept of fractional excess charge or filling anomaly. I will show how this concept is extended to two-dimensional systems in the case of obstructed atomic and fragile topological insulators.

Talk: Fractional charges in atomically precise lattices

21 Nov
14:30
15:30

Ingmar Swart

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Condensed matter can support quasiparticles with charges different than the electron charge e. The most well-known example is the Cooper pair, which consists of two electrons bound together and has an effective charge of $2e$. In a 2D electron gas with interactions under the influence of a strong magnetic field, quasiparticles with a fractional charge emerge (Fractional Quantum Hall effect). Shot-noise has been used to prove the existence of these quasi-particles [1]. Interestingly, in the presence of crystalline symmetries, certain topological insulators present a filling anomaly: a mismatch between the number of electrons in an energy band and the number of electrons required for charge neutrality. These filling anomalies can be considered quasi-particles with a fractional charge.

In my talk, I will show experimental realizations of two linear chains which exhibit filling anomalies: the SSH chain and the trimer chain. Using the tip of a scanning tunneling microscope, Cs and In adatoms were placed with atomic precision on a InAs(111)A surface. Clusters of adatoms locally bend the electronic bands, leading to the formation of particle-in-a-box like states. These artificial atoms can be coupled together to form lattices. Density of states measurements reveal the existence of localized quasi-particles. I would like to discuss the prospect of using shot-noise to measure the fractional charge of these quasiparticles.

[1] de-Picciotto *et al.*, Nature **389**, 162 (1997).

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22 Nov
9:00
10:00

Talk: Full Counting Statistics Probe of Local Correlations in Transport

Wolfgang Belzig

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The method of full counting statistics allows to identify the elementary charge transfer events and quantify the corresponding probabilities. This methods is developed for any quantum coherent conductor that may involve superconducting, magnetic or normal metal contacts [1]. In this talk, I will introduce the concept based on the extended nonequilibrium Keldysh Green's function technique and discuss it's application in illustrative examples [2]. The most recent ones involve on one hand the transport in so-called pico-contacts driven by ultrashort voltage pulses [3]. I will show that in the limit of pulses containing only a single oscillation, the relative phase of carrier and envelope can be detected in the fluctuations of the transported charge [4]. On the other hand, recently the interest in transport through magnetic impurities on superconductors, hosting so-called Yu-Shiba-Rusinov states or simply YSR states, has been pushed due to numerous experiments. To better understand recent measurements of the shot noise in a normal metal-YSR impurity contacts formed in a scanning tunneling microscope, we adapt a novel full counting statistics method [5] allowing to identify the details of the charge-resolved transport processes in this setting [6,7]. The methods also works with two superconducting contacts or even two YSR-impurities revealing a giant zoo of multi-charge transport processes.

[1] W. Belzig, *Full Counting Statistics of Superconductor–Normal-Metal Heterostructures*, in "Quantum Noise", ed. by Yu.V. Nazarov and Ya.M. Blanter (2002).

[2] M. Vanevic, Y. V. Nazarov, and W. Belzig, *Elementary Events of Electron Transfer in a Voltage-Driven Quantum Point Contact*, Phys. Rev. Lett. **99**, 225 (2007).

[3] M. Ludwig, G. Aguirregabiria, F. Ritzkowsky, T. Rybka, D. C. Marinica, J. Aizpurua, A. G. Borisov, A. Leitenstorfer, and D. Brida, *Sub-Femtosecond Electron Transport in a Nanoscale Gap*, Nat. Phys. **16**, 341 (2019).

[4] M. Hübler and W. Belzig, *Full Counting Statistics of Ultrafast Quantum Transport*, Appl. Phys. Lett. **123**, 034006 (2023).

[5] I. Snyman and Y. V. Nazarov, *Keldysh Action of a Multiterminal Time-Dependent Scatterer*, Phys. Rev. B **77**, 165118 (2008).

[6] U. Thupakula, V. Perrin, A. Palacio-Morales, L. Cario, M. Aprili, P. Simon, and F. Massee, *Coherent and Incoherent Tunneling into Yu-Shiba-Rusinov States Revealed by Atomic Scale Shot-Noise Spectroscopy*, Phys. Rev. Lett. **128**, 247001 (2022).

[7] D. C. Ohnmacht, W. Belzig, J. C. Cuevas, *Full counting statistics of Yu-Shiba-Rusinov bound states*, Phys. Rev. Res. **5**, 033176 (2023).

Talk: New insights from electronic transport in superconducting bound-states

22 Nov
13:30
14:30

U. Thupakula[1], V. Perrin[1], A. Palacio-Morales[1], L. Cario[2], M. Civelli[1], M. Aprili[1], F. Massee[1], **Pascal Simon**[1]

[1] *Laboratoire de Physique des Solides, University Paris-Saclay, CNRS, 91405 Orsay, France;*

[2] Institut des Matériaux Jean Rouxel, IMN, Université de Nantes, CNRS, F-44000 Nantes, France

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Majorana bound states are promising building blocks of forthcoming technology in quantum computing. Chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as such systems may host Majorana bound states. However, their non-ambiguous identification has remained a difficult issue because of the concomitant competition with other topologically trivial fermionic states, which poison their detection in most spectroscopic probes. I will theoretically show that the Fano factor, which is the ratio between shot noise and the current, turns out to be a very interesting and distinctive tool in that respect. In particular, the Fano factor tomography displays a spatially constant Poissonian value equal to one for Majorana bound states while it is strongly spatially dependent and exceeds one as a direct consequence of the local particle-hole symmetry breaking for other trivial fermionic in-gap states such as Yu-Shiba-Rusinov or Andreev ones. I will also show how shot noise can be used to reveal coherent and incoherent dynamics of an in-gap bound state associated to the presence of a magnetic impurity in a superconductor which sets the stage for a comparison with experimental shot noise data [2].

[1] V. Perrin, M. Civelli, P. Simon, Phys. Rev. B **104**, 121406 (2021)

[2] U. Thupakula, V. Perrin, A. Palacio-Morales, L. Cario, M. Aprili, P. Simon, F. Massee, Phys. Rev. Lett. **128**, 247001 (2022)

Talk: Tunnelling process into sub-gap states in NbSe2 revealed by atomic scale shot-noise

22 Nov
14:30
15:30

Freek Massee

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Isolated electronic states generated by single atom impurities, such as acceptor and donor states in semiconductors and in-gap states in superconductors, are ideal building blocks for bottom-up constructed devices. Particularly chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as they may host Majorana fermions. One of the challenges in this endeavour is to understand the intrinsic lifetime of the localised states, also known

as Yu-Shiba-Rusinov (YSR) states, which is expected to be limited by the inelastic coupling with the continuum. Here I will present how we used shot-noise scanning tunnelling microscopy combined with theoretical modelling to gain a deeper insight into YSR states in superconducting NbSe2 [1]. The current noise reveals the coexistence of both coherent and incoherent tunnelling processes into the in-gap states, and enables us to extract their intrinsic lifetime which is usually inaccessible to regular spectroscopy.

[1] U. Thupakula, V. Perrin, A. Palacio-Morales, L. Cario, M. Aprili, P. Simon, F. Massee, Phys. Rev. Lett. **128**, 247001 (2022)

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23 Nov
9:00
10:00

Talk: Josephson junctions with single magnetic adatoms

Martina Trahms[1], Larissa Melischek[2], Jacob F. Steiner[2], Bharti Mahendru[1], Idan Tamir[1], Nils Bogdanoff[1], Olof Peters[1], Gael Reecht[1], Verena Caspari[1], Clemens B. Winkelmann[3], Felix von Oppen[2], **Katharina J. Franke**[1]

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[2]*Fachbereich Physik and Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Germany*
[3]*Université Grenoble Alpes, CNRS, Institut Néel, Grenoble, France*

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Diode behavior in superconducting junctions describes the phenomenon of dissipationless current flow in one direction, while the current in the other direction underlies dissipation. Such non-reciprocal behavior has been found in Josephson junctions where inversion and time-reversal symmetry are broken. So far, most realizations are made of layered structures. Here, we create atomic-scale Josephson junctions in a scanning tunneling microscope and investigate their transport properties in the current biased mode. This allows characterization of the switching and retrapping currents, which separate the dissipationless from the dissipative branch. Plain Pb-Pb junctions show hysteretic and reciprocal behavior. By inserting single magnetic adatoms the retrapping current adopts nonreciprocity, mimicking diode behavior. We show that the nonreciprocity of the retrapping current depends on the particle-hole asymmetry of the Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap [1]. We extend the well-known resistively and capacitively shunted junction (RCSJ) model by assuming non-ohmic resistive behavior. The latter is mediated by the quasiparticle current flowing via Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap [1,2]. A full description of the junction behavior involves fluctuations in the junction, governing the statistics of the switching and retrapping currents. Apart from shot-noise measurements delivering information on the nature of charge transport across Josephson junctions, it is thus interesting to understand the influence of noise on transport behavior. We suggest measuring the response to noise as well as the intrinsic noise in the junction to understand the junction's dynamics fully.

[1] M. Trahms, L. Melischek, J. F. Steiner, B. Mahendru, I. Tamir, N. Bogdanoff, O. Peters, G. Reecht, C. B. Winkelmann, F. von Oppen, K. J. Franke, Nature **615**, 628(2023)

[2] J. F. Steiner, L. Melischek, M. Trahms, K. J. Franke, F. von Oppen, Phys. Rev. Lett. **130**, 177002 (2023)

Talk: How much noise is necessary in mesoscopic engines?

23 Nov
10:30
11:30

Ludovico Tesser

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Noise plays an important role in the characterization of nanoscale systems because, due to their small size, fluctuations are often comparable with average quantities. In this talk, I will discuss some general noise properties in coherent mesoscopic conductors. These properties can be formulated in the form of inequalities, setting bounds on the noise. For example, when the device works as an engine, it results in inequalities between the noise and useful output, *e.g.* output power.

First, I will introduce a novel relation between the average charge current flowing in a mesoscopic conductor and its noise [1]. Unlike the fluctuation-dissipation theorem, this inequality holds for arbitrary out-of-equilibrium conditions and approaches equality far from equilibrium. Furthermore, it reveals additional insights into the performance of nanoscale heat engines by setting a minimum amount of noise required to produce power, complementing the recently developed thermodynamic uncertainty relations [2]. However, heat is not the only resource that allows a nanoscale engine to produce a useful output. In the second part of the talk, I will introduce another property of noise in mesoscopic conductors. This relation establishes a constraint between the entropy production - as the resource of an engine - and its fluctuations, and provides the minimum noise required to produce or reduce the entropy [3]. This insight allows us to study the performance of various devices related to their fluctuations, including those exploiting nonthermal resources to produce a useful output.

[1] L. Tesser and J. Splettstoesser, *Out-of-Equilibrium Fluctuation-Dissipation Bounds*, arXiv:2309.17422.

[2] A. C. Barato, U. Seifert, *Thermodynamic Uncertainty Relation for Biomolecular Processes*, Phys. Rev. Lett. **114**, 158101 (2015)

[3] M. Acciai, L. Tesser, J. Eriksson, R. Sánchez, R. S. Whitney, J. Splettstoesser, *Constraints between entropy production and its fluctuations in nonthermal machines*, arXiv:2309.11570.

Talk: Magnetic impurities on superconducting proximitized metals

23 Nov
13:30
14:30

Jon Ortuzar Andres

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The formation of Yu-Shiba-Rusinov excitations in proximitized thin films is largely mediated by a type of Andreev-bound state named after de Gennes and Saint-James. We introduce a single-site model of the bound state coupled to a quantum spin and assess its adequacy by reintroducing the coupling to the continuum as a weak perturbation and studying its scaling flow using Anderson's poor man's scaling. This model is then exploited to understand the excitation spectrum of a Fe-porphyrin molecule on the Au/V(100) proximitized surface. We show that a single tunneling electron can excite a pair breaking excitation and prove that this novel excitation is a smoking gun to measure the local parity of the system. This combined experimental and theoretical research provides a new perspective on magnetic impurities in clean proximitized surfaces and their underlying physics.

Talk: Why shot noise does not generally detect pairing in mesoscopic superconducting tunnel junctions

23 Nov
14:30
15:30

Jiasen Niu

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The shot noise in tunneling experiments reflects the Poissonian nature of the tunneling process. The shot noise power is proportional to both the magnitude of the current and the effective charge q of the carrier. This can be used to detect electron pairing in superconductors [1,2]. Here, I will present our results that shot noise can be controlled by the transparency in superconducting tunnel junctions [3]. Remarkably, we find that shot noise corresponds to $q = 1e$ noise and thus does not reflect pairing in typical superconducting mesoscopic tunneling devices. We find that this is a consequence of the typical geometries of mesoscopic junctions. I will outline the potential for measuring shot noise in unconventional superconductors, and how we can tune transparency through the crossover from $1e$ to $2e$-noise.

[1] K. M. Bastiaans *et al.*, *Direct Evidence for Cooper Pairing without a Spectral Gap in a Disordered Superconductor above* T_c, Science **374**, (2021).

[2] Y. M. Blanter and M. Büttiker, *Shot Noise in Mesoscopic Conductors*, Phys. Rep. **336**, 1 (2000).

[3] J. Niu *et al.*, *Why shot noise does not generally detect pairing in mesoscopic superconducting tunnel junctions*, arXiv:2306.02397, (2023).

Poster: What are signatures of gapless superconductivity in proximitized topological insulators probed by local noise spectroscopy?

22 Nov
10:30
12:00

Jens Brede

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Recently, it was observed that a sufficiently strong supercurrent leads to a gapless superconducting state by the Doppler shift of the quasiparticle energy caused by finite Cooper pair momentum [1]. Such a 2D gapless superconducting state in spin-helical systems under the in-plane magnetic field host Majorana bound states when the topological 1D channels are formed by quantum confinement of quasiparticles via Andreev reflection [2]. First, we will show by STM/STS at 400 mK and in-plane magnetic fields of up to 2 T that a gapless state is realized in the topological surface state (TSS) of bismuth telluride [$Bi_2Te_3(0001)$] thin films grown on superconducting niobium [Nb(110)]. In zero magnetic field the STS on the top surface of the few nanometers thick Bi_2Te_3 films shows an induced hard superconducting gap of about 0.5 meV. Increasing the field, we observe in-gap states due to Doppler shifted Bogoliubov quasiparticles from the TSS which led to a zero bias conductance peak at a magnetic field of about 750 mT. At this field the induced screening current match the depairing current and quasiparticle interference at the Fermi energy shows distinct scattering vectors, demonstrating that segments of the normal-state Fermi surface are restored while still in the superconducting state. Thereafter, we will ask questions regarding signatures of this gapless state in local noise spectroscopy: What is the effective charge of the measured shot noise? What changes when probing putative Majorana modes? Can one perform (cross) correlation measurements using the STM-tip and our four sample contacts?

[1] Zhu *et al.*, Science **374**, 1381–1385 (2021)
[2] Papaj *et al.*, Nat. Commun. **12**, 577 (2021)

Poster: Shot-noise measurements of single-atom junctions using a scanning tunneling microscope

22 Nov
10:30
12:00

Verena Caspari[1], Idan Tamir[1], Daniela Rolf[1], Christian Lotze[1], and Katharina J. Franke[1]

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Current passing through small constrictions fluctuates due to the discreteness of charge. Measuring this so-called shot noise in atomic-scale superconducting junctions can provide valuable information, from the quanta of charge transferred in the tunneling process to the correlations of the involved tunneling channels. Here, we use a scanning tunneling microscope equipped with a high-frequency, low-temperature amplifier to measure simultaneously the noise characteristics and the differential

conductance of two types of Pb-Pb-junctions having different geometries. The first type is created by deposition and approaching single Pb adatoms, while the second type is established by a break-junction technique. We observe a correlation between the noise pattern and the strength of the Josephson current, independent on the method of junction preparation.

Poster: Introduction to local noise spectroscopic experiments

22 Nov
10:30
12:00

Jan Cuperus

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An MHz-frequency amplifier for STM setups, as introduced by Bastiaans [1] and Massee [2], is built into our Unisoku STM. It's performance is characterized by shot-noise measurements of Au(111) and $NbSe_2$ samples at 4.2 K and 330 mK, the results of which are presented in this poster. Additionally, challenges are identified and tentative experiments are proposed.

[1] K. M. Bastiaans *et al.*, *Amplifier for scanning tunneling microscopy at MHz frequencies*, Rev. Sci. Instrum. **89**, 093709 (2018)

[2] F. Massee *et al.*, *Atomic scale shot-noise using broadband scanning tunnelling microscopy*, Rev. Sci. Instrum. **89**,, 093708 (2018)

Poster: Correlated electron systems studied with local shot-noise measurements

22 Nov
10:30
12:00

Maialen Ortego

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Shot-noise measurements convey information about the effective charge of the carriers and their distribution in the tunnelling process. This provides unique information about a broad range of materials such as superconductors and fractional quantum Hall systems. In a superconductor, the shot-noise doubles inside of the superconducting gap due to Andreev reflection processes. Our simulations show that the energies at which the effective charge enhances, however, do not only depend on the gap magnitude, but also on the pairing symmetry or gap anisotropy. I will also discuss different scenarios for correlated electrons such as the intriguing interplay between magnetism and superconductivity, from Kondo systems to Shiba states, and the possible effect of dopants in semiconductors.

Poster: Tunneling signatures of the attractive Hubbard model

22 Nov
10:30
12:30

Bernhard Lüscher

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Shot noise measurements in an STM tunneling setup on the superconductor Titanium nitrid have given direct evidence of the pre-formation of cooper pairs in the pseudogap phase. We aim to better understand the noise signature of those preformed pairs on a theoretical level. To this end we examine the tunneling current in a transfer Hamiltonian approach between a metal and a superconductor, modelled by the attractive Hubbard model in the slave boson approximation. To obtain a noise signature of tunneling electron pairs, we aim to include higher order terms in the perturbative treatment of the transfer Hamiltonian.

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