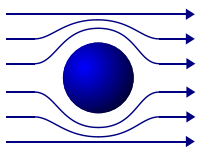


Annual Report
Jahresbericht

2009



WALTHER-MEISSNER-INSTITUT
für Tieftemperaturforschung
Bayerische Akademie der Wissenschaften



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Preface

The Walther-Meißner-Institute for Low Temperature Research (WMI) of the Bavarian Academy for Sciences and Humanities (BAdW) is looking back on a highly exciting year 2009. We successfully extended our efforts in research and teaching and have achieved an internationally leading position in several areas of low temperature research. On behalf of the members of WMI I am pleased to present our *Annual Report 2009*. The report is aiming to provide not only concise summaries of our ongoing research projects and their major results, but also information on our teaching activities as well as interesting data about publications, collaborations and recent developments in infrastructure and experimental facilities.

In 2009, the WMI was participating in several long-term, coordinated research programs jointly put into effect in collaboration with partners from both Munich universities and other national and international research institutions. In some of these programs the WMI is playing a leading role and providing the spokesman of the program. Besides our successful work in the *Collaborative Research Center 631* (Solid State Quantum Information Processing, see <http://www.wmi.badw-muenchen.de/SFB631>), the *Cluster of Excellence Nanosystems Initiative Munich* (see <http://www.nano-initiative-munich.de/>), the *Research Unit FOR 538* (High Temperature Superconductivity, see <http://www.wmi.badw-muenchen.de/FG538>), and the *DFG Priority Programs 1157* (Integrated Electroceramic Functional Systems) and *1285* (Semiconductor Spin Electronics), various other national and international research projects of WMI have been successfully continued in 2009 and promising new projects could be started. In particular, the WMI is participating in the new *Priority Program 1458* (High Temperature Superconductivity in the Iron-Pnictides) and the *Transregional Collaborative Research Center TRR 80* (From Electronic Correlations to Functionality), which both have been granted by the German Research Foundation and will start early in 2010.

Our successful research in 2009 is reflected in many excellent publications, new extramural funding, collaborations with industry, and many invited presentations at national and international conferences. The WMI also has organized national and international workshops and conferences, in this way promoting the research activities in low temperature physics. The total personelle of WMI, which has been about doubled within the last 10 years, meanwhile is reaching a saturation value around 70 people. The same is true for the outside funding, which was strongly increasing over the last decade and has meanwhile reached a high level well above 1 Mio EUR per year.

As the total personelle of WMI was increasing steadily over the last years, appropriate space for laboratories and offices has become an urgent problem. Fortunately, in 2009 WMI was able to get extra money from the state government within the so-called “Konjunkturpaket II”. This money will be used to establish the *WMI Quantum Science Laboratory* in the basement of the building, providing about 150 m² additional laboratory space. The planned laboratories are particularly suited for setting up new low temperature experimental facilities for ultra-sensitive studies on solid state quantum systems. The building activities already have been started in October 2009 and the new laboratories should become operational in late 2010.

A key factor for the high level of scientific productivity of WMI is the collaborative atmosphere, the commitment and high motivation of its research and technical staff as well as the support of various funding agencies. In this context we gratefully acknowledge financial support from the BAdW, the DFG, the Bavarian Ministry for Science and Arts, the BMBF and the EU. A further key to our success in research is the recruitment of outstanding, scientifically independent group leaders with complementary research interests and technical expertise, a process which

is supported and monitored by the scientific advisory board of WMI. In 2009, we recruited Hans Hübl, previously at the Centre for Quantum Computer Technology of the University of New South Wales, who is studying solid state systems for quantum information processing and nanomechanical systems. Furthermore, Frank Deppe joined the WMI quantum systems group to work on superconducting quantum circuits after finishing his doctoral thesis. Matteo Mariantoni left to UC Santa Barbara, after finishing his doctoral thesis and receiving a prestigious scholarship of the California Institute of Nanotechnology. Despite the continuous expansion of WMI, we are much committed to support and promote young scientists in their career.

The Annual Report 2009 is aiming to provide a general overview of the scientific results of WMI and to keep updated our friends and partners in research and industry. I hope that this report inspires your interest in WMI. I take this opportunity to thank all the colleagues, guests, students, post-docs and cooperating partners, who contributed to the success of our research and teaching activities within the last year, and last but not least all our friends and sponsors for their interest, trust and continuous support.



Rudolf Gross

Garching, December 2009



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The Walther–Meißner–Institute

General Information

The Walther–Meißner–Institute for Low Temperature Research (WMI) is operated by the Commission for Low Temperature Research of the Bavarian Academy of Sciences and Humanities (BAdW). The commission was founded in 1946 on Walther Meißner's initiative, who was president of BAdW from 1946 to 1950. The Commissions (Research Groups) of the Academy are set up in order to carry out long-term projects, which are too ambitious for the lifetime or capacity of any single researcher, or which require the collaboration of specialists in various disciplines. At present, the Bavarian Academy of Sciences and Humanities consists of 36 Commissions with more than 300 employees.

The Commission for Low Temperature Research of the BAdW started its research activities in 1946 in the Herrsching barracks. After the retirement of Walther Meißner in 1952, Heinz Maier-Leibnitz, who followed Walther Meißner on the Chair for Technical Physics of the Technische Universität München, became the new head of the Commission for Low Temperature Research. In 1967, the commission moved to the Garching research campus after the construction of the new "Zentralinstitut für Tieftemperaturforschung" (ZTTF) was completed (director: Prof. Heinz Maier-Leibnitz, technical director: Prof. Franz Xaver Eder). Until 1972, the theory group of the Institute Laue Langevin was hosted at the ZTTF. In 1980, Prof. Dr. Klaus Andres became the new director of the ZTTF again associated with the Chair for Technical Physics (E23) at the Technische Universität München, followed by Prof. Dr. Rudolf Gross in 2000. In 1982, the ZTTF was renamed into Walther-Meißner-Institute for Low Temperature Research (WMI) on the occasion of Walther Meißner's 100. birthday.

As already mentioned, it is a long tradition that the WMI also hosts the Chair for Technical Physics (E 23) of the Technische Universität München (TUM) with the director of the WMI being full professor at the Faculty of Physics of TUM. In addition, since 2004 the WMI also hosts a new scanning probe division with the head of this division being professor at the Ludwig-Maximilians-Universität (LMU). In this way a tight collaboration has been established between WMI and research groups of both Munich universities, joining technological and human resources in the fields of experimental and theoretical solid-state and condensed matter physics, low temperature techniques, materials science as well as thin film and nanotechnology. Noteworthy, the WMI supplies liquid helium to more than 25 research groups at both Munich universities and provides the technological basis for low temperature research.

Research Activities

The research activities of the Walther–Meißner–Institute are focused on low temperature solid-state and condensed matter physics (see reports below). The research program is devoted to both **fundamental** and **applied research** and also addresses **materials science, thin film and nanotechnology** aspects. With respect to **basic research** the main focus of the WMI is on

- superconductivity and superfluidity,
- magnetism and spin transport,
- quantum phenomena in mesoscopic systems and nanostructures,
- self-organization of molecules on surfaces,
- and the general properties of metallic systems at low and very low temperatures.

The WMI also conducts **applied research** in the fields of

- solid-state quantum information processing systems,
- superconducting and spintronic devices,
- oxide electronics,
- multi-functional and multiferroic materials,
- and the development of low and ultra low temperature systems and techniques.

With respect to **materials science, thin film and nanotechnology** the research program is focused on

- the synthesis of superconducting and magnetic materials,
- the single crystal growth of oxide materials,
- the thin film technology of complex oxide heterostructures including multi-functional and multiferroic material systems,
- the fabrication of superconducting, magnetic, and hybrid nanostructures,
- and the growth of self-organized molecular ad-layers.

The WMI also develops and operates systems and techniques for low and ultra-low temperature experiments. A successful development have been dry mK-systems that can be operated without liquid helium by using a pulse-tube refrigerator for precooling. Meanwhile, these systems have been successfully commercialized by the company VeriCold Technologies GmbH at Ismaning, Germany, which was taken over by Oxford Instruments in 2007. As further typical examples we mention a nuclear demagnetization cryostat for temperature down to below 100 μ K, or very flexible dilution refrigerator inserts for temperatures down to about 20 mK fitting into a 2 inch bore. These systems have been engineered and fabricated at the WMI. Within the last years, several dilution refrigerators have been provided to other research groups for various low temperature experiments. The WMI also operates a helium liquifier with a capacity of more than 150.000 liters per year and supplies both Munich universities with liquid helium. To optimize the transfer of liquid helium into transport containers the WMI has developed a pumping system for liquid helium that is commercialized in collaboration with a company.

To a large extent the research activities of WMI are integrated into national and international research projects such as Clusters of Excellence, Collaborative Research Centers, Research Units, or EU projects. The individual research groups of WMI offer a wide range of attractive research opportunities for diploma (graduate) students, PhD students and postdoctoral fellows.

Experimental Facilities and Resources

The WMI is equipped with state of the art facilities for the preparation and characterization of superconducting and magnetic materials as well as for various low and ultra-low temperature experiments. The main experimental and technological resources of WMI are listed in the following.

Materials Preparation and Fabrication of Nanostructures

- Laser Molecular Beam Epitaxy (L-MBE) system for oxide heterostructures (equipped with in-situ RHEED, Omicron AFM/STM system, atomic oxygen/nitrogen source, infrared-laser heating system, metallization)

- molecular beam epitaxy (MBE) system for metallic systems
- UHV magnetron sputtering systems for metals (e.g. Nb, Al, NiPd, ...)
- magnetron sputtering system for oxide heteroepitaxy (equipped with four sputtering guns and an oxygen ion gun)
- ion beam sputtering system
- reactive ion etching (RIE) system, Plasmalab 80 Plus with ICP plasma source, Oxford Instruments Plasma Technology
- ion beam etching (IBE) system equipped with a LN₂ cooled sample holder
- polishing machine for substrate preparation
- ultrasonic bonding machine
- 50 m² class 1000 clean room facility
- optical lithography (Süss maskaligner MJB 3 and projection lithography)
- electron beam lithography (based on Philips XL 30 SFEG scanning electron microscope and Raith Elphy Plus lithography system including a laser stage)
- four-mirror image furnace for crystal growth

Characterization

- 2-circle x-ray diffractometer (Bruker D8 Advance, sample temperature up to 1 600°C)
- high resolution 4-circle x-ray diffractometer with Göbel mirror and Ge monochromator (Bruker D8 Discover)
- scanning electron microscope with EDX analysis
- UHV room temperature AFM/STM system
- 2048 u high resolution mass spectrometer (Fa. Pfeiffer, cross beam ion source, SEM)
- Low Energy Electron Diffraction (SPECTA-LEED, Fa. Omicron)
- two Raman spectroscopy systems (1.5 to 300 K, in-situ sample preparation)
- SQUID magnetometer (Quantum Design, 1.5 to 700 K, up to 7 Tesla)
- several high field magnet systems (up to 17 Tesla) with variable temperature inserts
- 7 Tesla split coil magnet systems with optical access and variable temperature insert
- experimental set-ups for the measurement of noise including low noise SQUID amplifiers and signal analyzers
- high-frequency network analyzers (up to 40 GHz) and various microwave components (sources, mixers, circulators, attenuators) for the determination of high frequency parameters
- high-frequency cryogenic probing station (up to 20 GHz, $T > 4$ K)
- magneto-optical Kerr effect (MOKE) system
- ferromagnetic resonance (FMR) system

Low temperature systems and techniques

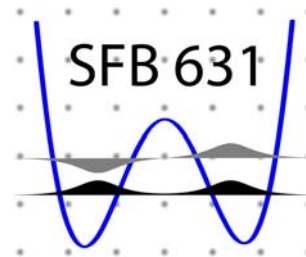
- 5 K-Scanning Tunneling Microscope (low temperature STM, Fa. Omicron)
- several ³He/⁴He dilution refrigerator inserts for temperatures down to 10 mK

- “dry” mK-cooler based on a dilution refrigerator with pulse-tube precooling
- ultra-low temperature facility for temperatures down to below $100\ \mu\text{K}$ based on a nuclear demagnetization cryostat
- experimental set-ups for the measurement of specific heat, magnetization, thermal expansion as well as electrical and thermal transport properties as a function of temperature, magnetic field and pressure

The Collaborative Research Center 631

Rudolf Gross, Achim Marx¹

The physics of solid state quantum systems is a key research field of Walther-Meißner-Institute (WMI). Hence, the Collaborative Research Center 631 (SFB 631) on *Solid State Based Quantum Information Processing: Physical Concepts and Materials Aspects* is one of the key research programs of WMI. It has been established in 2003 and a second four-year funding period has been granted by the German Research Foundation (DFG) in 2007. Within SFB 631, in 18 research projects subdivided into three research areas, research groups from the Bavarian Academy of Sciences and Humanities (BAdW), the TU Munich (TUM), the Ludwig-Maximilians-University (LMU), the Max-Planck-Institute for Quantum Optics (MPQ), as well as the University of Regensburg and the University of Augsburg are collaborating. It joins 35 principle investigators, more than 60 PhD and diploma students as well as a large number of postdocs and guest scientists. The WMI is one of the main actors within SFB 631, providing the coordination of the center from the beginning (spokesman: Rudolf Gross).



Within the project A3 on *Superconducting Quantum Circuits as Basic Elements for Quantum Information Processing* and project A8 on *Cavity Quantum Electrodynamics with Superconducting Devices*, the research program of WMI within SFB 631 is focussing on the fabrication and study of superconducting quantum information circuits. This includes the fabrication of superconducting flux qubits in which the quantum mechanical superposition states of clockwise and anticlockwise circulating persistent currents are used for the realization of solid state qubits. These qubits are coupled to superconducting microwave resonators. In this way fascinating quantum electrodynamic experiments with deliberately designed artificial solid state atoms become possible. Since such experiments are completely analogous to quantum optical experiments on natural atoms in optical resonators, this prospering new field is called circuit quantum electrodynamics (c-QED). Here, particular goals are the strong coupling of superconducting qubits to high-quality superconducting microwave resonators, the generation and detection of non-classical microwave Fock states, the development of dispersive readout and quantum non-demolition measurements, and the entanglement of superconducting qubits via multiple resonators. Regarding these research goals the WMI team closely collaborates with the theory groups at LMU (Marquardt, von Delft), the University of Augsburg (Hänggi, Reuther), the Universidad del País Vasco - Euskal Herriko Unibertsitatea at Bilbao (Solano), and the Canadian Institute for Quantum Computing at Waterloo (Wilhelm), as well as the experimental groups at the NTT Basic Research Laboratories (Semba) and the Nano Electronics Research Laboratories at NEC Corporation, Japan (Nakamura, Tsai, Yamamoto). The research work within SFB 631 is closely linked to the activities within Research Area C of the Cluster of Excellence *Nanosystems Initiative Munich (NIM)*.

Within the past year, the WMI team made very good progress in the fabrication and characterization of superconducting quantum circuits. Meanwhile the WMI team has established a reproducible fabrication process for superconducting flux qubits and the other circuit components (capacitors, inductors, resonators, beam splitters, etc.) required for c-QED experiments [1]. After having successfully studied the phase coherent dynamics of flux qubits in collaboration with the qubit group at the NTT Basic Research Laboratories in the previous years [2, 3], in 2009 the main focus was on c-QED experiments on flux qubits.

¹This work is supported by the Deutsche Forschungsgemeinschaft through SFB 631.

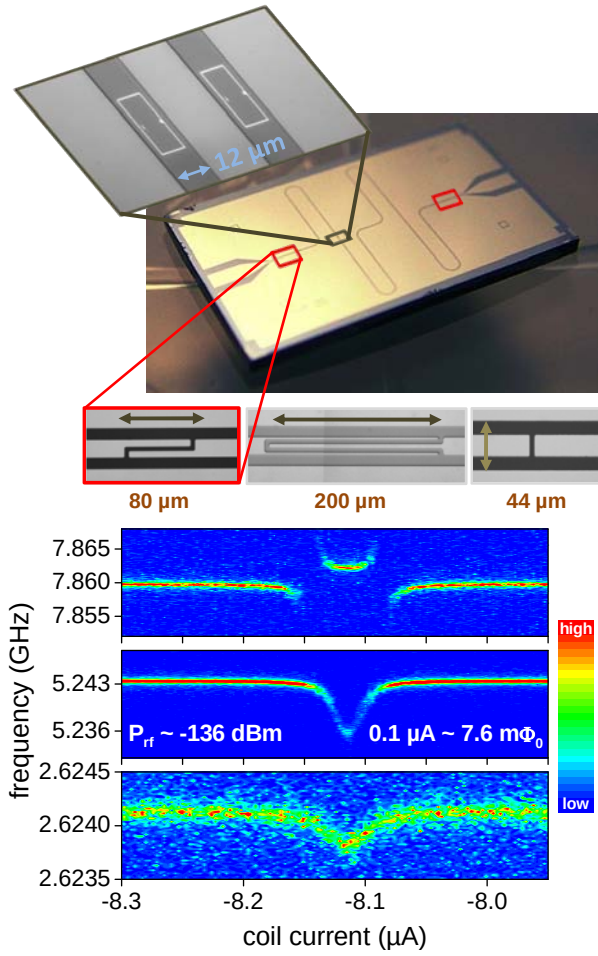


Figure 1: Top: Superconducting flux qubits embedded into the gap between the inner conductor and the ground planes of a coplanar waveguide (CPW) resonator. Also shown are different types of coupling capacitors. Bottom: Transmission spectrum of the CPW resonator as a function of the flux bias (coil current) of the qubit at the fundamental frequency and the first and second harmonic showing the level anticrossings and the dispersive shift due to the interaction with the qubit.

resonators via a qubit population inversion or by shifting the qubit operation point [6]. As shown in the report of Hoffmann *et al.* (see pp. 26–28), within the last year we made good progress in the implementation of the quantum switch. Furthermore, in collaboration with the theory group at Augsburg (Reuther, Hänggi) a detailed theoretical understanding for the dissipative two-resonator c-QED setup was established (see Ref. [7] and report of Deppe *et al.*, pp. 23–25).

In c-QED experiments it is necessary to investigate not only fields confined in cavities but also propagating states of the electromagnetic field, which for example are created, when a state is leaking out of a resonator. As shown in the report by Menzel *et al.* (see pp. 29–31) we made remarkable progress in the development of the experimental techniques for analyzing weak microwave signals on a single photon level at mK temperatures. These techniques have been successfully applied to perform a Planck spectroscopy experiment, which allows us to characterize microwave vacuum fluctuations as a function of frequency. Furthermore, we provided experimental evidence that such vacuum fluctuations represent the fundamental minimum quantum noise added by a beam splitter to any given input signal [8].

As shown in the report of Niemczyk *et al.* (see pp. 32–37), we successfully could perform c-QED experiments with 3-Josephson junction flux qubits placed in Nb microwave coplanar waveguide resonators. In these experiments the strong coupling regime could be achieved, with a coupling strength $g/2\pi$ well above 100 MHz at a qubit transition frequency of about 5 GHz and a resonator decay rate $\kappa/2\pi < 1$ MHz. Using these qubits we extended our experiments and theoretical analysis on two- and multi-photon qubit spectroscopy to get more insight into the fundamental symmetry properties of solid state quantum circuits and the non-linear dynamics inherent to c-QED. We recently showed that this can be exploited in a wide range of applications such as parametric up-conversion, generation of microwave single photons on demand or squeezing [4]. Together with the theory group of Solano, we were proposing a new and highly efficient read-out technique for superconducting qubits in the spirit of the electron shelving technique for trapped ions [5]. Our ideas can be adapted to different superconducting qubit designs and contribute to the further improvement of qubit readout fidelity.

We also designed a superconducting quantum switch based on two-resonator c-QED, permitting to switch on and off the interaction between the two microwave

We also performed cross-correlation measurements of statistical mixtures of weak propagating microwave signals [9]. To analyze the experimental data we developed a theory to derive all quadrature moments of propagating quantum microwaves

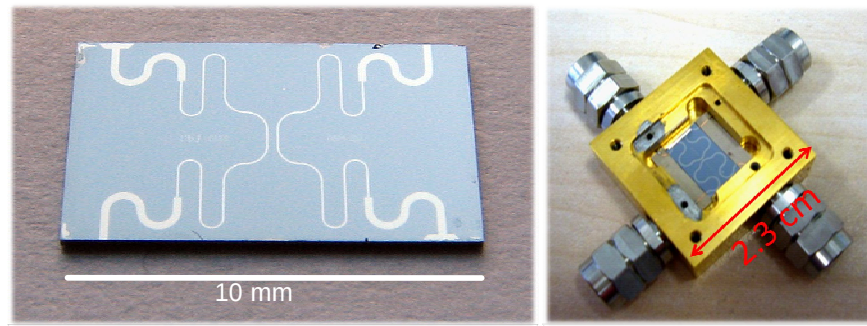


Figure 2: Top: Optical micrographs of the two resonators for the superconducting quantum switch. Bottom: The quantum switch chip mounted in the microwave sample holder.

using cross-correlations from a dual-path amplification setup. Moreover, we showed that the noise properties of the measurement device can be detected simultaneously, allowing the implementation of detector tomography. To illustrate our theoretical findings, we performed proof-of-principle experiments with various classical mixtures of coherent microwaves.

Finally, superconducting π -Josephson junctions with ferromagnetic interlayers have been successfully fabricated and characterized regarding their macroscopic quantum properties (see report by Wild *et al.*, pp. 41–43).

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The Nanosystems Initiative Munich – NIM

Rudolf Gross ¹

The physics and fabrication technology of solid state nanostructures has become a key activity in low temperature research. At WMI, quantum and correlation effects in hybrid mesoscopic structures consisting of superconducting, dielectric and magnetic materials are in the focus of several research projects, which are embedded into the Cluster of Excellence *Nanosystems Initiative Munich (NIM)*. A main activity addresses the fabrication, control/manipulation of magnetization direction, and spin transport in spin-nanosystems. Furthermore, the study of solid-state based quantum information systems and the development of novel nanoanalytical techniques are in the focus of our NIM projects. Within the past two years, a new activity directed towards the development of electro-mechanical nanosystems has been started in collaboration with the group of Tobias Kippenberg from Max-Planck-Institute for Quantum Optics (see report of Hocke *et al.*, pp. 19–22).



NIM is one of the Clusters of Excellence which have been established in 2006 by the German government's *Excellence Initiative*. Within NIM, scientists from various research facilities in the greater Munich area in the fields of physics, biophysics, physical chemistry, biochemistry, pharmaceuticals, biology, electronics and medicine are collaborating. The overriding goal is to design, produce and control a series of artificial and multi-functional nanosystems. The cluster joins research groups from LMU Munich, TU Munich, WMI, the University of Augsburg, the Munich University of Applied Science, the Max-Planck-Institutes for Biochemistry and Quantum Optics, and the Deutsches Museum. NIM is aiming to realize and study nanosystems interfacing the worlds of information and communication systems on the one hand and life sciences and medical nanotechnology on the other hand. Nanosystems are already playing a major role in information and communication systems: the electronic components in computers and communication technology are becoming smaller and smaller. However, this development cannot go on forever, once the nanometer scale has been reached. At that level, novel physical phenomena often arise that may present potential problems for conventional uses – and an opportunity for innovations and new applications. Micro- and nanosystems are also becoming increasingly important in the life sciences and medicine. They can be introduced to living organisms, for instance to bring a cancer medication to tumor cells. “Programmed drug delivery” is therefore one of the ten research areas within NIM. Other research areas focus on quantum phenomena in nanosystems, connecting nanosensors to living cells and “lab on a chip” applications.

The WMI actively participates in the research program of NIM in the research areas A: *Single Electron and Spin Nanosystems* (R. Gross, S.T.B. Gönnerwein), C: *Quantum Information Nanosystems* (R. Gross, A. Marx), and F: *Nanoanalytics and Enabling Techniques* (B.A. Hermann). In *Research Area A* (coordinated by Rudolf Gross, WMI), our research activities are focusing on the fabrication and characterization of spin-nanosystems, as well as on complex hybrid nanosystems composed of normal metals (N) and correlated electron materials (e.g. superconductors (S), ferro- (F) and antiferromagnets (AF)). Regarding the former, the key goal is the control and manipulation of magnetization as well as the study of spin transport in magnetic nanosystems. To this end, considerable progress has been achieved within the last

¹This work is supported by the German Excellence Initiative via the Nanosystems Initiative Munich (NIM).

A new research field started at WMI about two years ago is nanomechanics. Over the last few years opto-mechanical systems have become a topic of considerable interest. In such systems nano-mechanical harmonic oscillators are coupled to the electromagnetic field inside a suitable cavity. At sufficiently strong coupling, such systems may allow to explore various quantum effects such as superposition and entanglement, or the generation of cat states at a macroscopic scale. Furthermore, they may allow to perform ultra-sensitive measurements on macroscopic objects or to combine opto-mechanical systems in the microwave regime with nonlinear circuit elements such as Josephson junctions or qubits. In a collaboration between the NIM research areas A, C, and D we have fabricated electro-mechanical nanosystems consisting of a superconducting nanobeam coupled to a high quality factor superconducting microwave resonator. As shown in the report by Hocke *et al.*, (pp. 19–22) such systems have been successfully fabricated at WMI. Superconducting microwave resonators with fundamental frequency around 5 GHz and quality factors of the order of 50 000 have been fabricated. The superconducting Al nanobeam have been studied using a magnetomotive detection scheme. They showed resonance frequencies up to about 100 kHz which are still too low. To improve the situation, the fabrication of nanobeams based on Nb and SiN has been started.

In **Research Area F**, the research focus is on the development of novel nanoanalytical techniques based on functionalized cantilever arrays that act as extremely sensitive and specific receptors for (bio)chemical substances.

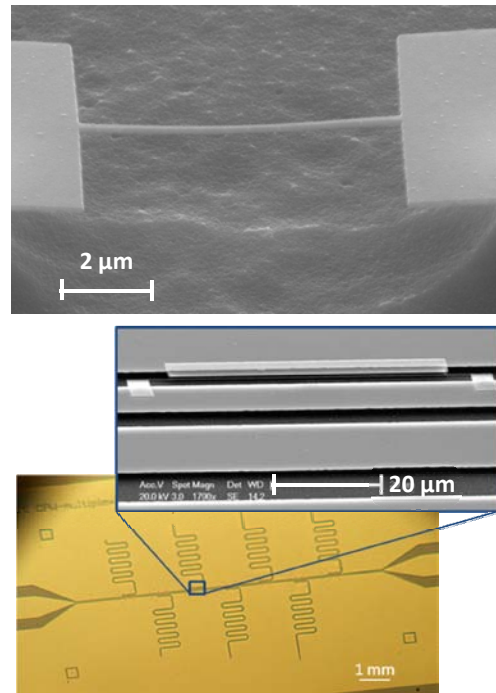


Figure 2: Top: Scanning electron microscopy micrograph of an about 200 nm wide a superconducting Al nanobeam suspended on a Si wafer using a reactive ion etching. Bottom: Micrograph of a suspended nanobeam coupled to a microwave resonator (meander-shaped structure), which itself is coupled to a microwave transmission line.

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The iron age of superconductivity: German Science Foundation starts new Priority Program 1485

Rudi Hackl^{1,2}

High-temperature superconductivity in compounds with iron? Nobody was ready to believe that before Yoichi Kamihara and coauthors in Hideo Hosono's group discovered a transition at $T_c=26$ K in $\text{La}(\text{O}_{1-x}\text{F}_x)\text{FeAs}$ [1]. Since the publication of the results in 2008 more than thousand papers have appeared, and the highest T_c so far exceeds 50 K. Even though the materials contain arsenic or other rather toxic elements many laboratories started with the preparation of poly- and single-crystalline samples. Generally, the Fe atoms form two-dimensional layers and are coordinated with atoms from the N column in most of the cases (with Se as an exception) as shown in Fig. 1. For this reason the family name pnictides (*Pn*) is used. In particular Chinese scientists contributed a lot of important results and found $\text{Nd}(\text{O}_{1-x}\text{F}_x)\text{FeAs}$ with the so far highest transition at 55 K [2]. While in the beginning many people believed the iron pnictides to be another class of oxides Dirk Johrendt and his group [3] demonstrated that high transition temperatures can also be obtained in purely intermetallic compounds. At optimal doping with $x \approx 0.4$ $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ reaches a T_c of 38 K. In contrast to the oxifluorides (see Fig. 1) large single crystals can be grown although the homogeneity and the quality is not in all cases satisfactory. However, crystals of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ and LaFePO are already sufficiently clean for the observation of quantum oscillations [4, 5].

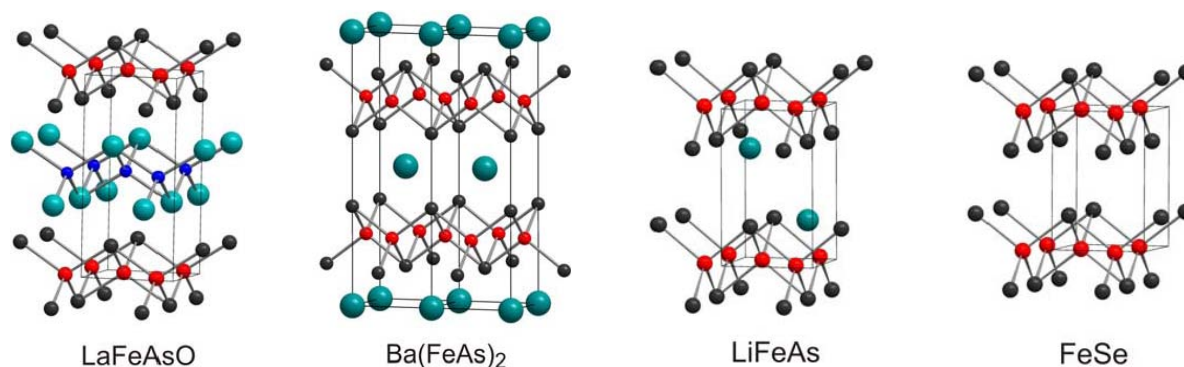


Figure 1: Structures of iron pnictide compounds (by courtesy of D. Johrendt). $\text{LaFeAsO}_{1-x}\text{F}_x$ (1111; $T_c^{\text{max}}=28$ K) was the first pnictide superconductor with high T_c [1]. With Pr, Nd or Sm replacing La T_c exceeds 50 K [2]. $\text{LaFeAsO}_{1-x}\text{F}_x$ is isostructural to LaFePO having the transition at 6 K at the stoichiometric composition. BaFe_2As_2 (122) develops a spin-density wave (SDW). When doped with K for Ba [3], Co for Fe [6] or P for As the SDW is suppressed and superconductivity appears. LiFeAs (111) has a maximal T_c of 18 K. The simplest of the materials, FeSe (11), with the same structural elements but Se for As has a maximal T_c of 8 K with 9% Se deficiency at ambient pressure and reaches 27 K at 1.5 GPa [7, 8].

The question for the origin of superconductivity arose immediately. Are the iron pnictides similar to the cuprates or to MgB_2 with $T_c=39$ K due to electron-phonon coupling or are they a material class on their own? The spin-density-wave (SDW) order of the parent compound indeed suggests a proximity to the cuprates, where the superconducting phase emerges from a Mott insulator. With doping p away from half filling spin and charge fluctuations as well as superconductivity follow antiferromagnetic long range order. In contrast to the cuprates, there is no universal phase diagram in the pnictides (Fig. 2). In the essentially hole-doped oxifluorides there is an abrupt transition from a magnetically ordered phase to a superconducting one,

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²The title is borrowed from a Viewpoint by Michelle Johannes in *Physics* 1, 28 (2008).

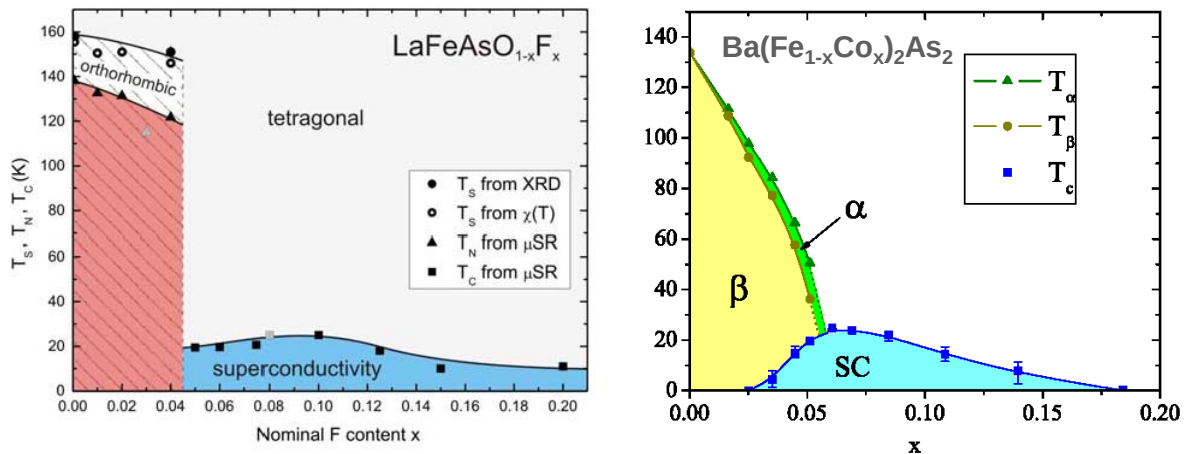


Figure 2: Phase diagrams of $\text{LaFeAsO}_{1-x}\text{F}_x$ (left) [10] and $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ (right) [9]. While SDW und superconductivity (SC) overlap in 122 there is a strict separation in La-1111. The structural transition at T_α always precedes spin density wave order at T_β .

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with T_c only weakly depending on doping. The electron-doped intermetallic compounds have a smooth transition, and SDW order and superconductivity may even coexist [9]. The phase boundary of superconductivity is dome-shaped.

The differences in the phase diagrams of the pnictides are surprising since the electronic structures are remarkably similar. There are 5 bands derived from the Fe 3d orbitals. Two ($\alpha_{1,2}$) form concentric hole-like Fermi cylinders around the center of the Brillouin zone (BZ), two ($\beta_{1,2}$) have FSs which encircle the corner of the small BZ derived from the 2Fe crystallographic unit cell (Fig. 3). Since the cross sections of the resulting Fermi surfaces are nearly equal the α and β sheets are nested with the vector $\mathbf{Q} \simeq (\pi, \pi)$. Consequently, the electronic susceptibility, described by the Lindhard function, becomes strongly peaked at the nesting vector $\mathbf{Q}$ [11] and is therefore believed to be at the origin of the SDW. The pronounced peaks in the susceptibility make the strong variations of the properties upon small changes of the electronic and lattice structures at least plausible.

The real part of the susceptibility is also considered a possible origin of superconductivity [11–14] while the electron-phonon coupling is probably weak [15]. From this point of view, the pnictides and the cuprates appear to be cousins in the same family even if the strong metallicity of the parent phases of the FePn compounds may argue otherwise. But how can the coordinates of the pnictides be determined? In a recent optical transport study the authors conclude from the reduced band width that the pnictides are half way between normal metals and the cuprates [16]. However, the related spectral redistribution to be expected upon doping is not observed by angle-resolved photoemission (ARPES) and x-ray absorption (XAS) [17, 18]. Perhaps one of the most telling similarities would be if the pnictides had the signature property of all cuprates – an energy gap $\Delta_{\mathbf{k}}$ having nodes and a sign change along the Fermi surface [19].

So far there is no experimental clarity about the electronic many-body properties of the pnictides. While a resonance in the spin correlation has been observed [21] which may be traced back to the susceptibility the search for the gap structure yields no unified picture yet. However, it seems a safe statement that non of the theoretical proposals is realized in its pure beauty. It appears that the bulk sensitive methods are more compatible with a strong modulation of $\Delta_{\mathbf{k}}$ some even indicating true nodal behavior [22, 23]. ARPES and Andreev tunneling, on the other hand, favor large, essentially constant gaps on all Fermi surfaces [24, 25]. The possible anisotropies in the superconducting state are accompanied by band-dependent carrier dynamics in the normal state as observed by quantum oscillatory phenomena [4, 5] and the analysis

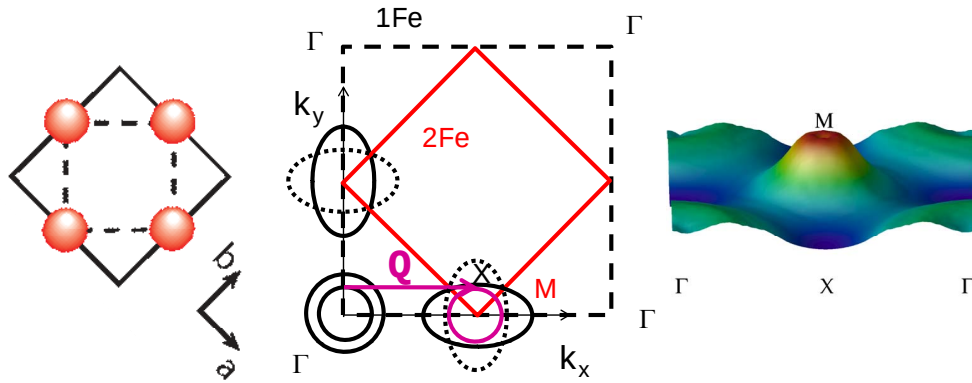


Figure 3: Iron plane (left), Brillouin zone (BZ), and real part of the non-interacting susceptibility $\chi_0(\mathbf{q}, \omega)$ [11] (right) of FePn materials. The cell relevant for the electronic structure contains 1 Fe atom (dashes) and is smaller by a factor of 2 and rotated by 45° with respect to the crystal cell (full line and axes a and b). The BZ of the unit cell (full line) and the first quadrant of the Fe plane (dashed line) are shown along with the FS cross sections at $\pi/c=0$ (adopted from Ref. [20]). The dotted FSs are obtained by downfolding the 1 Fe BZ. Even with the ellipsoidal elongation of the M barrels the α and β bands are approximately nested. $\text{Re}\chi_0(\mathbf{q}, \omega)$ controls the pairing strength [11].

of Hall data [26]. For the clarification of these fundamental questions at the heart of the physics of the pnictides bulk sensitive spectroscopies with band and momentum resolution will be instrumental (see contribution by Muschler *et al.* in this annual report).

It became apparent relatively early that the pnictides are much harder a problem to solve than, e.g., MgB_2 . In fact, electron-spin or direct electron-electron interactions moved into the main focus of research. Therefore, the people working on the CuO_2 compounds were naturally attracted. As a consequence a new DFG Priority Program (SPP 1458) was initiated by scientists from Dresden [Büchner (IFW)], Aachen [Honerkamp (RWTH)], and München [Johrendt (LMU), Hackl (WMI)] and will be funded for expectedly 6 years starting in April 2010. The WMI is participating with one project (Hackl, Gross). The Priority Program will be interdisciplinary with chemists and physicists contributing. The objective is to combine broad expertise for optimizing samples, typically single crystals, and for paving the way towards novel materials which may be useful for applications. In a sense this is a reaction to the fact that the undoped parent compounds of both the cuprates and the pnictides were well known quite some time ahead of the first observation of superconductivity in doped variants.

The discovery of superconductivity in the pnictides redirected part the research activities away from the cuprates. Nevertheless, the DFG Research Unit on “Properties of CuO_2 superconductors” (FOR538) stayed focused. One of the highlights is the first observation of quantum oscillations in $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ ($x=0.15, 0.16$, and 0.17), an electron-doped cuprate [27] (see also contribution by Helm *et al.*, pp. 68–71). Similarly as on the hole-doped side [28] the Fermi surface undergoes a transition from a small to a large cross section which can be a result of the formation of small correlation-induced pockets at low doping. The extremely high quality of the crystals grown at the WMI (see contribution by Erb *et al.*, pp. 91–94) was at the origin of this important result.

The Research Unit on the cuprates will expire on June 30, 2010. In April 2010, an international workshop will be organized by the WMI using the facilities of the Academy in the Munich Residence to share the results on both cuprates and pnictides with leading experts and to prepare a smooth transition between the two DFG programs. The hope is that the new results in the pnictides pave the way also towards a better understanding of the cuprates and of high-temperature superconductivity in general.

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Quantum experiments in electromechanical systems

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Optomechanical systems are systems where a mechanical harmonic oscillator is coupled to the electromagnetic field inside a suitable cavity. The cooling of mechanical modes by the light field in the cavity is hereby of particular interest. In principle, even cooling to the quantum mechanical ground state of the vibrational mode is possible, allowing for investigation of quantum mechanics in a literal sense [1]. Another interesting field of research is the design of ultra-sensitive measurements of a macroscopic object. Furthermore, the combination of optomechanical systems in the microwave regime with nonlinear circuit elements such as Josephson junctions or qubits open a new playground. Both systems have already been coupled to nanomechanical resonators [2, 3].

Until today, many different approaches have been considered for the realization of an optomechanical system. For example, the interaction of the radiation pressure of a light field inside a cavity with the vibrational degree of freedom of a movable micro-mirror [3–7] or a membrane inside the cavity [8] have been used. In another attempt, the coupling between the radiation field of a whispering gallery mode of a toroidal micro-cavity and of a microsphere with its particular vibrational mode has been successfully employed [9, 14].

Recently, Regal *et al.* [10] have coupled a superconducting on-chip microwave transmission line resonator capacitively to a mechanical resonator (nanobeam) on a chip. The motion of the nanobeam modulates the resonance frequency of the microwave transmission line resonator, almost in the same way as the optical resonance is shifted by the mechanical motion in the usual optomechanical setups. The approach of using resonators in the microwave regime instead of optical cavities is very promising. It allows to perform on-chip measurements of optomechanical effects at cryogenic temperatures. The nanomechanical resonator is much lighter than the typical micro-mirrors. Moreover, it is not necessarily constrained to be larger than the radiation wavelength, and it is naturally strongly coupled to the microwave resonator. Rocheleau *et al.* [11] could cool the flexural mechanical mode of a nanobeam in a similar setup to an average occupation number of less than 4. This is the lowest occupation number achieved in optomechanical systems so far.

Following the approach of Regal *et al.* [10], we started to design a hybrid design consisting of a microwave resonator fabricated from niobium and a nanobeam fabricated from aluminum. The advantage of using niobium is the higher T_c compared to aluminum. We can characterize the resonators at temperatures of liquid ^4He . Resonators made from niobium are expected to yield higher quality factors at millikelvin temperatures compared to aluminum resonators because of the lower reduced temperature T/T_c of niobium resulting in a lower thermal quasiparticle density. Furthermore, we expect higher cooling rates due to the fact, that niobium sustains higher current densities in its superconducting state compared to aluminum.

Figure 1(a) shows an optical micrograph of a typical sample. Seven quarterwave resonators with differing eigenfrequencies are capacitively coupled to a microwave feedline. To pattern the structures, a 100 nm thick niobium layer is sputtered on a silicon wafer, followed by an optical lithography process and a reactive ion etch (RIE). We designed microwave resonators with quality factors up to 70 000 at temperatures of 1.5 K.

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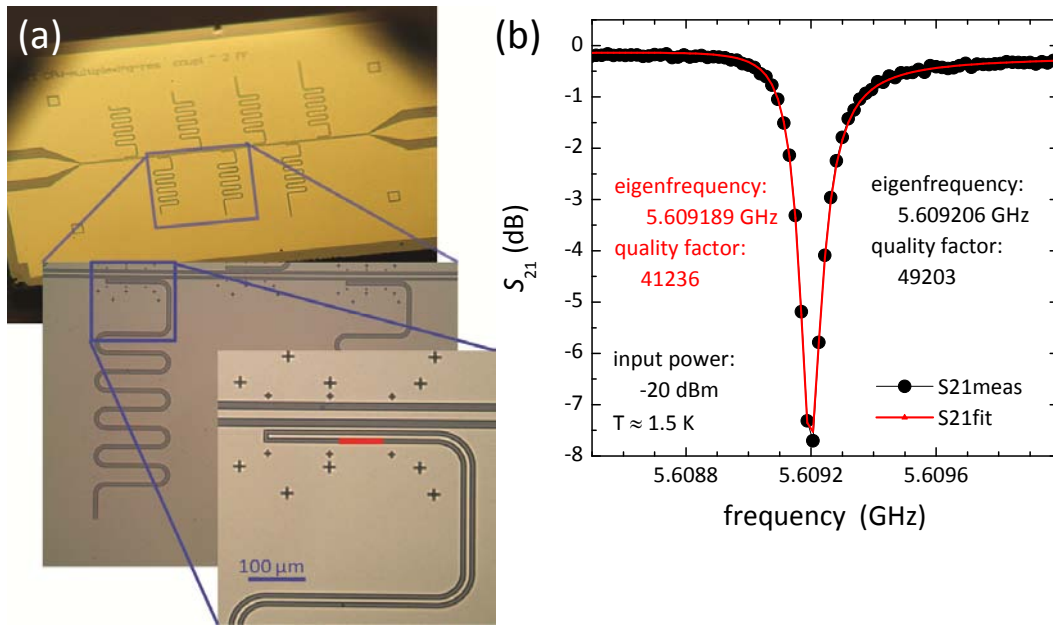


Figure 1: (a) Optical micrographs of a chip. The microwave cavities are coupled to a microwave transmission line. They are meandered to fit on the chip. The red mark indicates the position of the beam. (b) shows a typical spectrum of one microwave resonator. The black dots correspond to experimental data, the red line is a Lorentzian fit function.

Figure 1(b) shows a transmission experiment for one of the resonators. Off resonance the transmission through the feedline is approx. -0.3 dB, corresponding to a transmissivity of approximately 0.93. On resonance, the microwave resonator starts to absorb power from the transmission line. Fitting this Lorentzian lineshape results in a quality factor of 41236.

The mechanical resonators are structured in a subsequent step onto the microwave resonator using electron beam lithography techniques [cf. Fig. 2(a)]. The beam itself is galvanically coupled to the center conductor of one of the microwave resonators at a location with an antinode of the electric field. Since the coupling of the mechanical resonator is mediated capacitively, the

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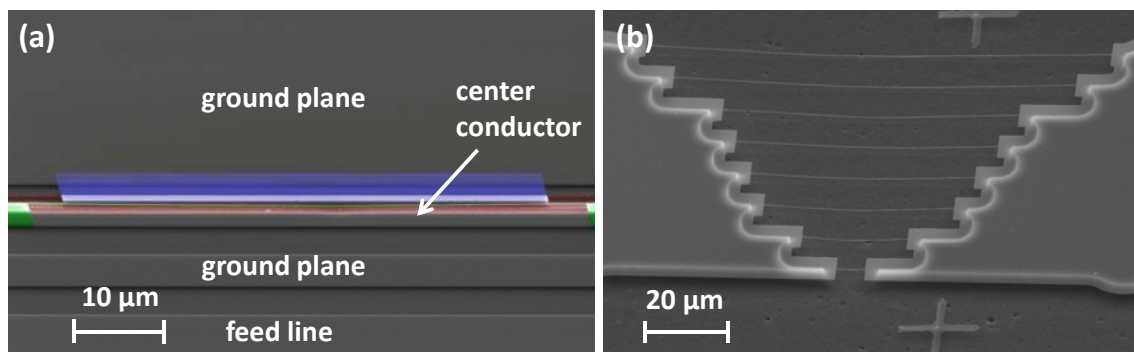


Figure 2: (a) Optical micrograph of a $60\text{ }\mu\text{m}$ long, suspended nanobeam (green) coupled to the center conductor of a microwave cavity. (b) shows a typical harp arrangement of eight nanobeams used to optimize the fabrication techniques and the eigenfrequencies of beams with different lengths.

To optimize the beam fabrication process we use a simpler structure than the full optomechanical approach discussed above. By fabricating nanobeams on a “harp” arrangement as shown in Fig. 2(b), it is possible to investigate the eigenfrequencies and fabrication techniques for various material systems. Figure 3(a) shows the resonance frequency of one beam at different applied magnetic fields. The beam’s motion is detected using a magnetomotive detection scheme [16]. Figure 3(b) shows the amount of power absorbed by beams with different lengths, driven at their particular eigenfrequencies as function of the applied magnetic field. In this particular experiment, the aluminum beams have not been annealed to release the compressive stress in the beam, resulting in relatively low resonance frequencies. The quality factors are low due to the beam operation in He vapor. Using this approach, a nano-crystalline diamond beam was fabricated. Here, an additional Al layer was deposited afterwards to allow magnetomotive and capacitive detection of the beam motion. Diamond itself has very promising material parameters with respect to density and stiffness to allow for high frequency beams. Furthermore, when properly doped a superconducting state can be reached below 2 K [15].

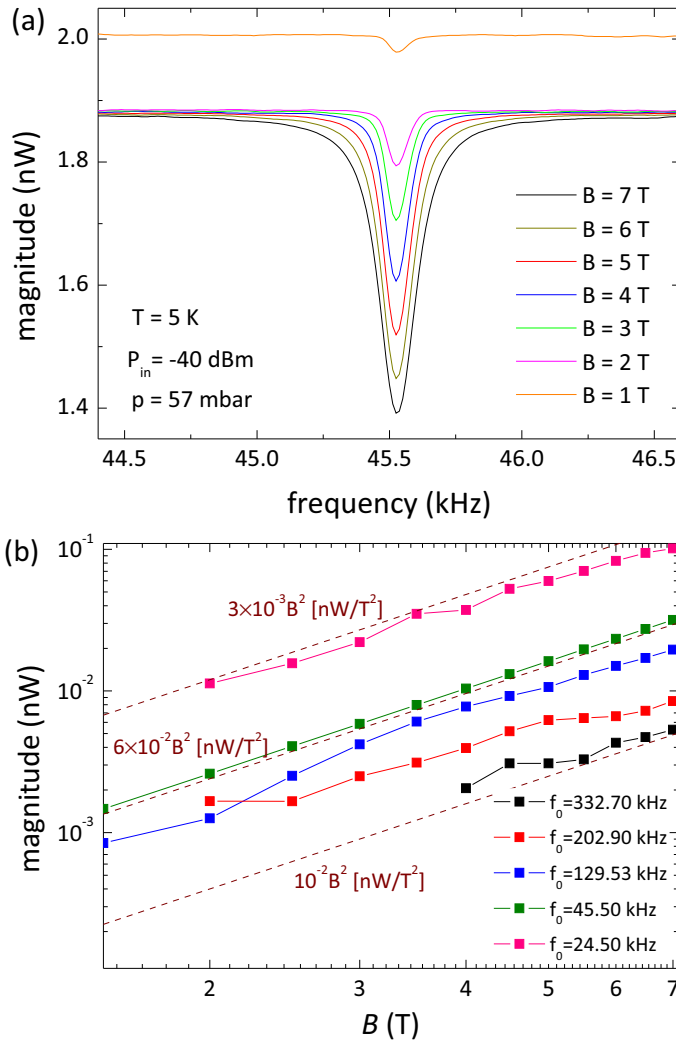


Figure 3: (a) Typical absorption spectrum of a nanobeam measured with a magnetomotive detection scheme. (b) Magnitude of the absorption of various beams plotted versus the applied magnetic field.

coupling and to read out the mechanical motion of a nanobeam coupled to a microwave resonator.

Coming back to the optomechanical hybrid structure, in first experiments with this system at 1.5 K a detection of the beam motion was not achieved. This possibly originated from too weak coupling of the beam to the microwave resonator. In order to improve the optomechanical coupling of beam and microwave resonator, we started to produce samples, where the microwave resonator and the mechanical oscillator are fabricated from the same Nb layer. To increase the eigenfrequency of the nanobeam an additional, highly tensile stressed SiN layer is used. This should allow for easier detection of the mechanical motion at a temperature of 1.5 K.

In summary, we managed to build first optomechanical samples. We detected mechanical motion of nanobeams using a magnetomotive detection scheme in a harp structure and produced nanomechanical oscillators from SiN (so far without niobium) and nano-crystalline diamond, respectively. In the next step, we are planning to demonstrate the optomechanical

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Two-resonator circuit quantum electrodynamics: Dissipative theory

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The interaction of light and matter on a quantum level is of substantial interest in both fundamental physics [1] and quantum information processing [2]. Experimentally, this topic was addressed in quantum-optical cavity quantum electrodynamics (QED) [3, 4], where single or multiple natural atoms (“matter”) were subjected to the light field inside a three-dimensional cavity. A few years ago, it turned out that analogous experiments can be performed with superconducting circuits patterned on silicon chips. In this so-called circuit QED [5, 6], on-chip microwave resonators replace the cavities and Josephson-junction-based circuits act as artificial atoms, which can be approximated as quantum two-level systems or qubits [7–9] in most cases. These possess a large effective dipole moment [10], allowing not only for strong [6, 11], but even for strong second-order [12] qubit-resonator coupling. In this context, the term strong coupling refers to the situation, where the qubit-resonator coupling coefficient is larger than all relevant decay rates in the system.

Motivated by these results and with the scalability potential inherent to circuits on a chip in mind, we developed a second-order scheme for switchable coupling between two superconducting resonators mediated by a superconducting flux qubit [10, 13]. In this so-called quantum switch setup [14–16], the resonator-resonator coupling coefficient has a first- or second-order geometric and a qubit-state dependent second-order dynamical contribution. While the former stems from the circuit nature of the qubit, the latter allows for switching the coupling on or off by controlling the qubit in a suitable way [14]. However, since we are dealing with a solid-state system, we have to take decoherence processes into account. In flux qubits, these can be dominated by either energy relaxation or the loss of phase coherence, depending on the working point [17]. The decay rates of microwave resonators can be well controlled by proper engineering [10]. However, for designing successful quantum switch experiments, a detailed understanding of the quantum coherence properties of the coupled two-resonator-qubit system is essential. To this end, we develop a theoretical treatment for the dissipative behavior of the quantum switch setup in two-resonator circuit QED [18]. We derive an effective Hamiltonian beyond the rotating-wave approximation and study the dissipative dynamics within a Bloch-Redfield quantum master equation approach. We show analytically how the qubit affects the quantum switch even if it has no dynamics and estimate the strength of this influence. Our analytical results are corroborated by numerical calculations. The details can be found in Ref. [18], information on current experimental progress in Ref. [16].

We start from the dissipationless quantum switch Hamiltonian in the laboratory basis, the physical basis of the circuits and fields,

$$\mathcal{H}' = \frac{\hbar\epsilon}{2}\sigma'_z + \frac{\hbar\delta_Q}{2}\sigma'_x + \hbar\Omega(a^\dagger a + b^\dagger b + 1) + \hbar G(a + a^\dagger)(b + b^\dagger) + \hbar g\sigma'_z(a + a^\dagger + b + b^\dagger). \quad (1)$$

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Here, δ_Q is the qubit tunnel matrix element and ε the bias, which can be tuned by means of the externally applied flux [13, 17]. σ'_x and σ'_z are the Pauli operators. The total qubit level splitting is $\omega_{qb} = (\delta_Q^2 + \varepsilon^2)^{1/2}$ and both resonators have the same angular frequency Ω . The coefficients g and G describe the strength of the qubit-resonator interaction and that of the geometric coupling between the two resonators, respectively (cf. Fig.1). The influence of the dissipation is modeled by adding bosonic baths to the Hamiltonian of Eq. (1). These are assumed to be mutually independent and couple to the relevant degrees of freedom of qubit and resonators [18]. In the quantum switch setup, the qubit is strongly detuned from the resonators ($\Delta = \omega_{qb} - \Omega \gg g$) and there exists a switching protocol, where the qubit remains in its ground state all the time [14]. In this situation, we can trace out the qubit degrees of freedom and write down an effective quantum master equation for the resonator-resonator interaction,

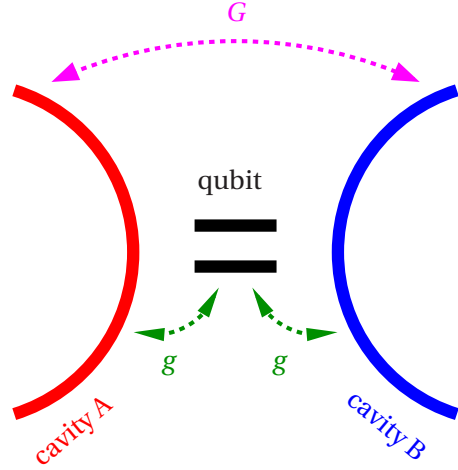


Figure 1: Schematic sketch of the quantum switch setup.

$$\dot{\rho}_{\text{cav}} = -\frac{i}{\hbar} [\mathcal{H}_{\text{cav}}^{\text{eff}}, \rho_{\text{cav}}] + \kappa_A \mathcal{D}[a] \rho_{\text{cav}} + \kappa_B \mathcal{D}[b] \rho_{\text{cav}} + \kappa_{\text{qb}} \mathcal{D}[a+b] \rho_{\text{cav}}. \quad (2)$$

Here, ρ_{cav} is the two-resonator density operator, $\dot{\rho}_{\text{cav}}$ its time derivative, $[X, Y] = XY - YX$ the commutator of the operators X and Y , $\mathcal{D}[X] \rho_{\text{cav}} = X \rho_{\text{cav}} X^\dagger - (1/2)[X^\dagger X, \rho_{\text{cav}}]_+$ the Lindblad dissipation operator, $[X, Y]_+ = XY + YX$ the anticommutator of X and Y , and $a, b, a^\dagger, b^\dagger$ are the annihilation and creation operators of the two resonators. Furthermore,

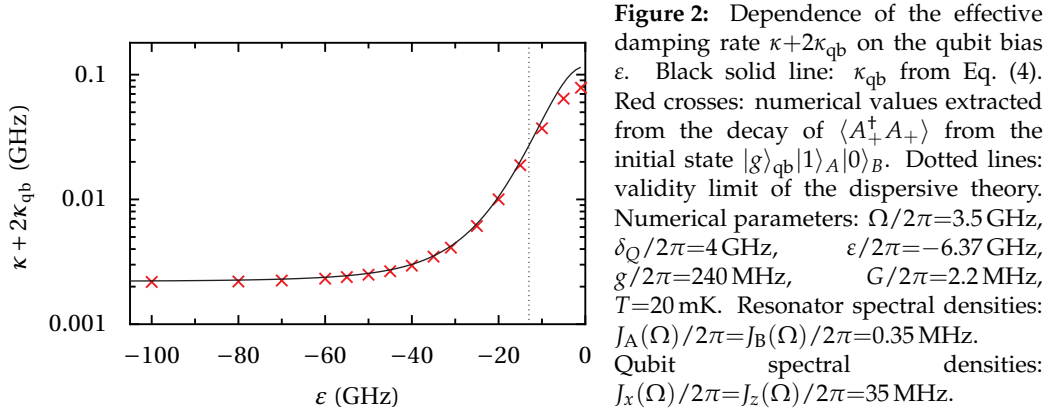
$$\mathcal{H}_{\text{cav}}^{\text{eff}} = \hbar \Omega (a^\dagger a + b^\dagger b + 1) - \hbar (\lambda_\Delta^2 \Delta + \lambda_\Sigma^2 \Sigma) (a^\dagger a + b^\dagger b + 1) + \hbar g_{\text{SW}} (ab^\dagger + a^\dagger b) \quad (3)$$

is the second-order two-resonator Hamiltonian, $\lambda_\Delta = (g \sin \theta) / \Delta \ll 1$, $\lambda_\Sigma = g (\sin \theta) / \Sigma \ll 1$, $\Sigma = \omega_{qb} + \Omega$, $\theta = \arctan(\delta_Q / \varepsilon)$ is the qubit mixing angle, and $\sin \theta = \delta_Q / \omega_{qb}$. The effective resonator-resonator coupling strength, $g_{\text{SW}} = G - (\lambda_\Delta^2 \Delta + \lambda_\Sigma^2 \Sigma)$, depends on the qubit operating point via ω_{qb} . We find it noteworthy to mention that the appearance of Σ and λ_Σ in Eq. (3) is due to the fact that a rotating-wave approximation is not made at the level of the first-order Hamiltonian of Eq. (1), but in the second-order Hamiltonian just before arriving at Eq. (3) [18].

In addition to the decay rates κ_A and κ_B of the two resonators, Eq. (2) shows a third qubit-induced decay channel affecting the “center-of-mass mode” $A_+ = a + b$. The associated rate is

$$\kappa_{\text{qb}} = (\lambda_\Delta + \lambda_\Sigma)^2 [J_x(\Omega) \cos^2 \theta + J_z(\Omega) \sin^2 \theta], \quad (4)$$

where $\cos \theta = \varepsilon / \omega_{qb}$. The spectral densities $J_{x,z}$ characterize the influence of the baths coupling to the qubit via $\sigma'_{x,z}$. Equation (4) constitutes the central result of this work. In particular, we note that the expression for κ_{qb} is very similar to that for the energy relaxation rate of the bare qubit, $\gamma = J_x(\omega_{qb}) \cos^2 \theta + J_z(\omega_{qb}) \sin^2 \theta$ [18]. This indicates that the latter affects the quantum switch operation. However, its deteriorating influence is strongly reduced by the factor $(\lambda_\Delta + \lambda_\Sigma)^2$, which reflects the fact that we are dealing with a second-order process. When inspecting an extended version of Eq. (2), we further find that qubit dephasing becomes important only in fourth order. Altogether, we expect the quantum switch setup to be robust against qubit-induced dissipation over a wide range of operating points independent of the dominating decoherence channel. Finally, we confirm the validity of the analytical expressions of Eq. (3)



and Eq. (4) with numerical simulations (cf. Fig. 2). We find excellent agreement as long as the strong-detuning condition holds.

In conclusion, we develop a theory for dissipative two-resonator circuit QED. We provide an analytical effective quantum master equation for a strongly detuned qubit mediating a controllable interaction between two on-chip microwave resonators. We find that this quantum switch is useful even with today's limited qubit coherence times.

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Two-resonator circuit QED: Experiments

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In circuit quantum electrodynamics (QED) [1, 2], electrical circuits exhibiting quantum mechanical properties at the macroscopic level interact analogously to the way light and matter do in quantum-optical cavity QED [3, 4]. More precisely, in our experiments the “light” is a standing microwave generated in a suitable LC harmonic oscillator, whereas the “matter” is represented by nonlinear superconducting quantum circuits based on nanoscale Josephson-junctions. These act, when suitably designed, as quantum mechanical two-level systems or qubits [5]. Since circuit QED systems are inherently tunable by electromagnetic fields and have a great potential for scalability, they are considered useful tools for quantum information processing [6] and for testing fundamental quantum mechanics “on a chip”. Along this line, among several other exciting experiments, two superconducting qubits have been successfully coupled to a coplanar waveguide resonator [7] employing an off-resonant second-order coupling scheme. Because of the strong effective dipole moment of the qubits, the qubit-resonator coupling coefficients can be made much larger than all relevant inverse lifetimes and the resonator effectively mediates a well-detectable, to some extent tunable coupling between the qubits. Inspired by this result, we recently suggested a dual experiment: the *quantum switch* setup. There, a qubit mediates a second-order coupling between two microwave resonators [9]. Depending on the qubit state, the resonator-resonator coupling can be either on, off, or a superposition of the two. In the latter case, Schrödinger cat or Greenberg-Horne-Zeilinger states [10] can be created. However, before realizing the complex structure of the quantum switch setup, the properties of two degenerate superconducting on-chip resonators with resonance frequencies of a few gigahertz and a fixed coupling coefficient need to be understood.

In this work, we report on the initial steps on the way to realize the quantum switch using a superconducting flux qubit [8], which is the qubit realization used at the WMI [11, 12]. To this end, we first investigate the coupling of two superconducting stripline resonators on a chip. We study the transmission properties and demonstrate the appearance of a non-negligible second-order contribution to the resonator-resonator coupling coefficient when inserting a superconducting loop between two galvanically separated resonators.

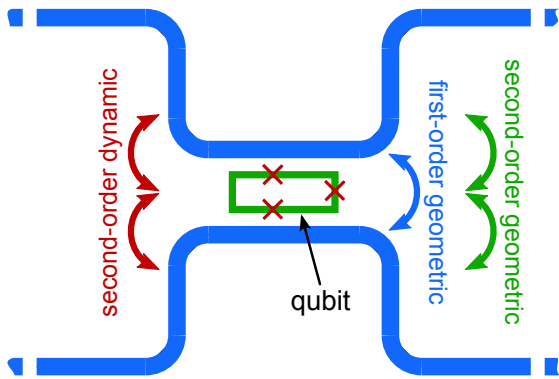


Figure 1: The quantum switch setup: two resonators (blue) coupled via a flux qubit. The red crosses mark the Josephson junctions. The arrows represent the resonator-resonator coupling channels.

Each of our superconducting on-chip microwave resonators consists of a niobium transmission line segment with length ℓ , which is connected to the measuring transmission lines by a coupling capacitor C_c at each end. The resonance frequency and decay rate can be engineered by choosing suitable values for ℓ and C_c , respectively [13]. Two resonators can be coupled either via their mutual inductance or capacitance, depending on whether the magnetic or the electric field component is used. Since the flux qubit is sensitive to the former, we consider only inductive coupling from hereon. A system of two degenerate superconducting resonators is an essential ingredient for the quantum switch introduced in 2008 by M. Mariani

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et al. [9]. In addition, a superconducting flux qubit, which is detuned from the resonator frequency, has to be strongly coupled to both resonators. To this end, it may be placed near the current antinodes of the fundamental modes as shown in Fig. 1. This configuration gives rise to three coupling channels between the resonators: a first- and second-order geometric, as well as a qubit-mediated second-order “dynamic” coupling. Since the latter changes sign when the qubit flips its state, the coexistence of geometric and dynamic coupling gives rise to a controllable resonator-resonator interaction. One specific prerequisite for a such a quantum switch is that the sum of first- and second-order geometric coupling between the two resonators has to be comparable to the second-order dynamic coupling. This can be satisfied by choosing a 400 μm long coupling region, where the two resonators are 100 μm apart.

In order to study the geometric coupling only, we first insert a superconducting $100 \times 300 \mu\text{m}^2$ niobium loop instead of the flux qubit between the resonators. In Fig. 2, transmission data for typical samples are shown. The results can be explained by the standard theory of two degenerate coupled harmonic oscillators, where the uncoupled frequency $\omega_0/2\pi$ is split into the two nondegenerate coupled modes $\omega_{\pm} = [\omega_0(\omega_0 \pm g)]^{1/2}$. In our samples, $\omega_0/2\pi = 4 \text{ GHz}$. After inserting a loop which is not connected to the resonators, the total geometric coupling coefficient g increases by more than 50%. Employing galvanic loop-resonator coupling even yields a 200% increase, although the double-peak structure shifts slightly to higher frequencies. This considerable increase provides clear evidence for the presence of a significant second-order geometric coupling when the loop is present. Consequently, our samples will allow for the detailed study of geometric second-order coupling effects in a setup based on superconducting flux quantum circuits.

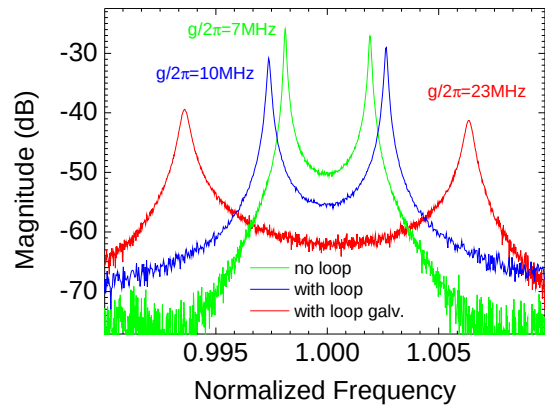


Figure 2: Transmission spectra measured through ports from different resonators at 4.2 K. The frequency is normalized over $\omega_0/2\pi$. Green curve: two resonators only. Blue curve: a superconducting loop emulating a flux qubit is inserted between the two resonators. Red curve: the loop is galvanically coupled to the resonators (slight shift of double-peak structure corrected for clarity).

In conclusion, based on the experimentally observed coupling strengths, we expect the successful operation of a quantum switch using the resonator layout discussed in this report. In the next step, we are planning to replace the superconducting loop by a flux qubit consisting of a $100 \times 300 \mu\text{m}^2$ aluminum loop interrupted by four nanoscale Josephson junctions. These qubit loops are significantly larger than the typical sizes of $10 \times 5 \mu\text{m}^2$ currently used at the WMI [11, 12]. First experiments to study their properties are in progress.

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Cross-correlation measurements of statistical mixtures of weak propagating microwaves

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The interaction between matter and light plays a central role in the realm of cavity QED, in which a real atom interacts with the electromagnetic field inside a cavity. Concepts developed for the optical domain have been transferred and applied to the microwave regime, establishing the fast evolving field of circuit QED. There, superconducting quantum circuits, acting as tunable, artificial atoms (qubits), are strongly coupled to the microwave field of a superconducting transmission line resonator [1]. As demonstrated in the seminal work of M. Hofheinz *et al.* [2], non-classical states of the electromagnetic field can be generated and detected inside a resonator via a qubit with a high level of control. For a deeper understanding of the properties of microwave radiation it is necessary to investigate not only fields confined in cavities but also propagating states of the electromagnetic field, which for example are created, when a state is leaking out of a resonator. However, concepts like optical homodyning in the quantum regime for the measurement of propagating states rely on the existence of detectors with single photon resolution. Unfortunately, the smaller energy scale of microwave radiation prevents processes used in the optical domain to detect photons. This lack of suitable detectors in the frequency range of 1 to 10 GHz has driven the development of a cross-correlation measurement scheme [3], which can resolve the mean value and variance of propagating microwave fields with minimum noise disturbance. Weak microwave signals can be amplified using high electron mobility (HEMT) amplifiers, but these amplifiers obscure the signal with noise on the order of 10 to 20 photons on average (poa). Nevertheless, we show that the signals can be recovered by splitting and the subsequent amplification using two independent chains. In this way, the inevitably added noise χ during the amplification process can be canceled using cross-correlation techniques.

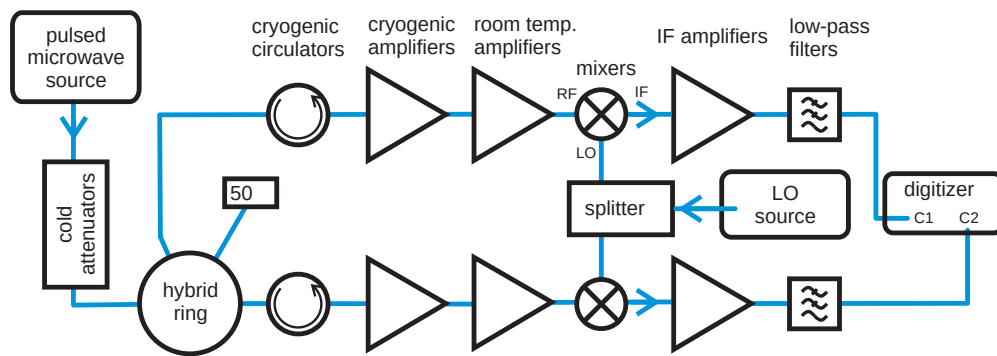


Figure 1: Experimental setup. The signal is split by a microwave hybrid and fed into two independent amplification chains. After down conversion by a mixer and amplification it is digitized and processed.

One particular constituent of the signal variance, the second moment $\langle S^2 \rangle$, is contaminated by the amplifier noise in the case of a single amplification chain because $\langle \chi^2 \rangle \gg \langle S^2 \rangle$. However, using two distinct amplification chains allows one to replace the second moment by the

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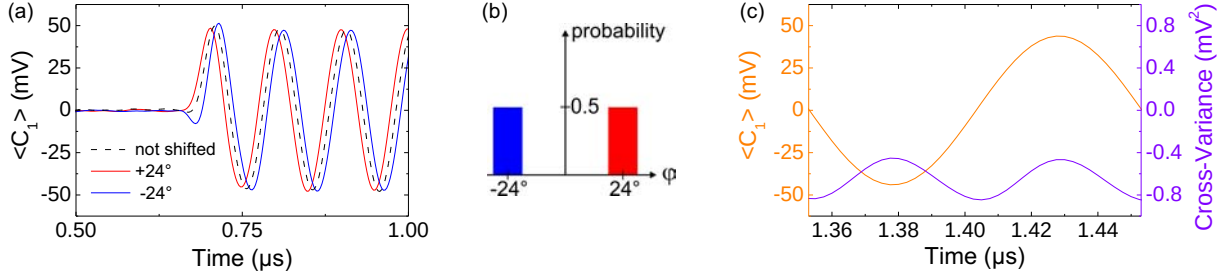


Figure 2: Time-dependent variance. (a), mean value of phase shifted pulses. (b), histogram of the statistical mixture. (c), mean value (orange) and cross-variance (violet) of the signal mixture after 10 million averages. The power at the hybrid's input is -124 dBm (100 poa). Similar results are retrieved for 10 poa

cross-product. In this case, the noise contributions of the two amplifiers cancel since they are uncorrelated, $\langle \chi_1 \chi_2 \rangle = 0$ (the index refers to the individual chain). Previously, we have demonstrated that our setup is capable to detect the mean value of pulsed coherent microwaves down to power levels of 10^{-20} W equivalent to 0.001 poa. The resolution limit for the variance is between 1-2 poa [4]. Here, we describe a further characterization of our experimental setup (see Fig. 1) with statistical mixtures of phase shifted microwave pulses with a carrier frequency of 5.85 GHz. Part of the setup is located in a dilution refrigerator. The pulsed microwaves are damped by cold attenuators cleaning the signal from room temperature thermal noise. Then the signal is split by means of a hybrid ring, which acts as a beam splitter for microwaves. This four port device does not only ensure a balanced division of the signal with minimum loss, but also provides an isolation of approximately 40 dB between its output ports. This, together with the isolation of the cryogenic circulator makes sure that noise from one cold amplifier can not enter the other amplification chain. Thus, the amplification chains act as truly independent noise sources. In order to sample the amplitudes with high resolution, the signals are down converted with mixers to a frequency of 10 MHz. Details on the amplification chain, circulators and mixers can be found in [5].

One aim of our setup is to retrieve a time-dependent variance signal, which is not meaningful for deterministic signals. There $\langle f^2(t) \rangle - \langle f(t) \rangle^2 = 0$ holds (brackets denote ensemble averaging) and one has to investigate statistical mixtures of signals instead. Here, we are using phase shifted signals, whose mean value for left (red) or right (blue) shifts is displayed in Fig. 2(a). To retrieve these curves, only pulses with a distinct phase shift are sent into the input line and the experiment is repeated for the other phase shift. A statistical mixture with an equally distributed histogram [see Fig. 2(b)] is formed by a train of pulses that are alternatively shifted to left and to the right. A simple statistical analysis shows that in this case the mean value is again a sinusoidal, $A \sin \omega t \cos \phi$, and that the cross-variance is time-dependent: $-A^2 \cos^2 \omega t \sin^2 \phi$, with the phase shift ϕ and the frequency $\omega/2\pi = 10$ MHz after down conversion. The measurement for a carrier power level equivalent to 100 poa and a phase shift of $\phi = \pm 24$ deg is plotted in Fig. 2(c). The cross-variance oscillates with twice the frequency of the mean value as a result of the squaring.

Furthermore, we try to detect the third central moment, which is a measure of the asymmetry of a histogram. Our experimental results are summarized in Fig. 3. On the left the case of an equally distributed histogram is displayed, where the according third central moment trace is flat. Skewing the histogram by shifting one fourth of the pulses to the left and the rest to the right results in an oscillating third central moment signal, displayed in Fig. 3(b).

In conclusion, we show that our setup is capable to detect time-dependent variances of statistical mixtures of phase shifted weak microwave signals. Furthermore, we demonstrate the

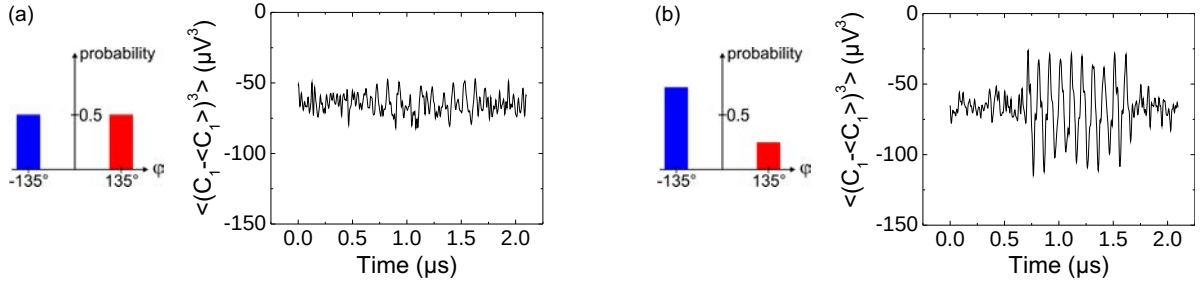


Figure 3: Third central moment. (a), equally distributed histogram and according measurement of the third central moment. (b), in the case of a skewed histogram a third central moment signal is coming up. The power at the hybrid input is -124 dBm and the number of trace averages is 10 million.

detection of a third central moment. In other words, we have developed a tool to fully describe Gaussian states, e.g. squeezed states, and to check a state for being non-Gaussian by considering its third moment. A further promising application of this tool is the investigation of entanglement of the electromagnetic fields inside two resonators, whose mutual coupling is mediated by a flux qubit [6].

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Reaching the strong coupling regime with superconducting flux qubits

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The interaction between light and matter at the quantum level has been intensively studied in the field of cavity quantum electrodynamics (QED) at optical frequencies during the last decade. In these experiments atoms are placed inside a cavity with highly reflective mirrors. The atoms interact via their dipole moments with the (quantized) electromagnetic field inside the cavity at a rate g - the interaction or coupling rate. In the strong coupling regime this interaction rate g is larger than both, the photon loss rate of the cavity κ and the atom decay rate γ .

In 2004, the strong coupling regime was for the first time realized experimentally in a solid-state architecture [1] by coupling a superconducting (SC) qubit to a quasi-1D superconducting microwave transmission line resonator. In comparison to cavity QED experiments with natural atoms in optical cavities, the main advantage of this new field - often referred to as *circuit QED* - is the large electric or magnetic dipole moment of these “artificial atoms”, the *in-situ* tunability, and the small cavity mode volume. At the WMI we focus on superconducting flux qubits placed in properly designed superconducting resonators. In this report we show spectroscopic measurements that demonstrate that the strong coupling regime can be readily accessed both for inductive and galvanic coupling.

The SC flux qubits [2] consist of a SC ring interrupted by three nanometer-sized Josephson junctions (JJ) (see Fig. 1(c)). At low temperatures, the flux qubit effectively behaves as a two-level system with transition frequencies $\omega_q/2\pi \sim 2\text{--}7\text{ GHz}$ from the ground state $|g\rangle$ to the excited state $|e\rangle$. The qubits are fabricated by electron beam lithography and Al shadow evaporation techniques. The SC transmission line cavities for our experiments are fabricated on thermally oxidized silicon wafers by dc-magnetron sputtering of Nb (200 nm) and patterned by optical lithography and reactive ion etching. Figure 1(d) shows an optical image of a SC coplanar waveguide (CPW) resonator. The length of the central conductor defined by the two discontinuities (coupling capacitors) in Fig. 1(a) determines the fundamental resonance frequency ($\lambda/2$ mode). Figure 1(b) shows the measured transmission spectra for the first three modes of a slightly over-coupled CPW resonator and the corresponding quality factors. The quality factor $Q = \omega_r/\kappa$ is directly proportional to the photon lifetime in the cavity and is mainly determined by the value of the coupling capacitors. For highly under-coupled CPW resonators, we achieved quality factors up to 2.5×10^5 at $\omega_r \sim 2\pi \times 1.25\text{ GHz}$.

Strong coupling limit with inductively coupled flux qubits

The system of a flux qubit inductively coupled to a CPW resonator as shown in Fig. 1(d) is conveniently described by the Jaynes-Cummings-Hamiltonian

$$\hat{H} = \hbar\omega_r \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right) + \frac{\hbar}{2}\omega_q + g \left(\hat{a}^\dagger \sigma_- + \hat{a} \sigma_+ \right) \quad , \quad (1)$$

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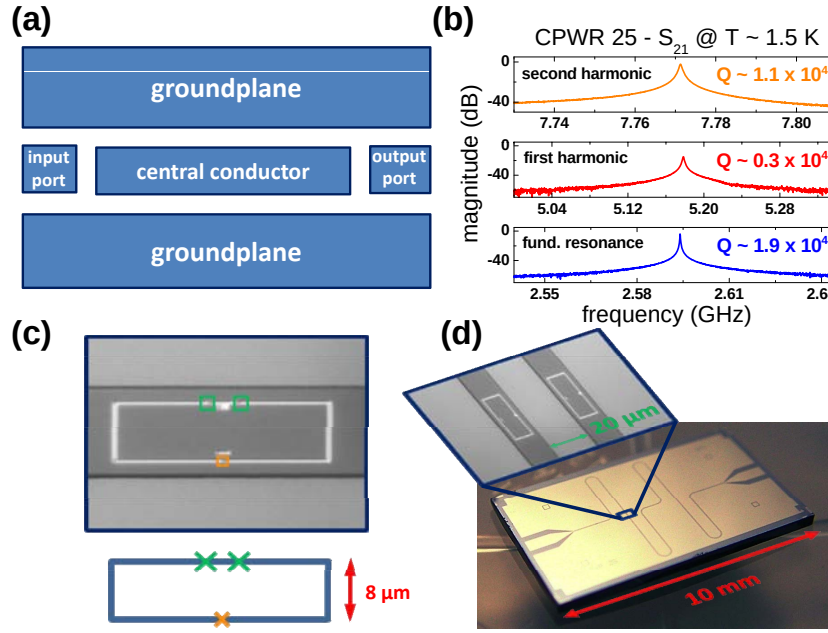


Figure 1: (a) Schematic of a CPW resonator. The two coupling capacitors in the central conductor at the input and output ports act as ‘mirrors’ for the electromagnetic field inside the cavity. The photon loss rate of the cavity κ is mainly determined by the value of these coupling capacitors. (b) Transmission spectra for a slightly over-coupled CPW resonator. The plot shows the first three modes, also indicating the measured quality factor $Q=\omega_r/\kappa$. (c) Optical image and schematic of a 3-JJ flux qubit. Two of the junctions have an area A while one of the junctions is smaller by a factor $\alpha\sim 0.6-0.8$. Typical junctions areas are of the order $200\times 100\text{ nm}^2$. (d) Optical images of a CPW resonator and two flux qubits located in the gap on opposite sides of the central conductor. The loop area of the qubits is approximately $30\times 8\text{ }\mu\text{m}^2$. During fabrication, the flux qubits have to be placed at an antinode of the standing magnetic field (maximum current) of the respective CPW mode in order to maximize the coupling g .

where fast oscillating terms were neglected using a rotating-wave approximation. The first term is a harmonic oscillator modeling one resonator mode, the second term is the qubit transition energy, and the third term proportional to the coupling g represents the qubit resonator interaction. The qubit transition frequency $\hbar\omega_q=\sqrt{\Delta^2+\epsilon^2(\Phi)}$ can be tuned by an external flux bias. The quantity ϵ is related to the persistent current I_p circulating in the qubit loop and is given by $\epsilon(\Phi)=2I_p\Phi_0[\Phi/\Phi_0-(n\pm 1/2)]$ where n is an integer. Thus, $\epsilon(\Phi)=0$ at the qubit degeneracy points $\Phi=\Phi_0(n\pm 1/2)$.

The measurements are performed in a dilution refrigerator at a temperature of $\sim 15\text{ mK}$. Our setup is shown schematically in Fig. 2(a). Using a highly attenuated probe tone ω_{rf} from a vector network analyzer we monitor the transmission through our cavity depending on an external flux bias Φ . Figure 2(b) and Figure 2(c) show the measured transmission spectra in a color-coded image. When the detuning $\delta=\omega_q-\omega_r=0$, the individual eigenstates of the cavity ($|0\rangle, |1\rangle, \dots$) and the qubit ($|g\rangle, |e\rangle$) are no longer eigenstates of the coupled system. Instead, the new eigenstates of the system are symmetric and antisymmetric superpositions $(|g\rangle|1\rangle\pm|e\rangle|0\rangle)/\sqrt{2}$, a combination of cavity photons and qubit excitations. This leads to an avoided crossing – the vacuum-Rabi splitting – at $\delta=0$ with an energy level separation given by $2\hbar g$. The data is shown in the top panels of Fig. 2(b) and Fig. 2(c) and clearly shows that we are in the strong coupling limit $g>\kappa, \gamma$.

When $\delta\gg g$, the system is in the dispersive regime. In this regime, qubit and resonator are still coupled through a second-order term g^2/δ in the dispersive Hamiltonian

$$\hat{H} \approx \hbar \left(\omega_r + \frac{g^2}{\delta} \sigma_z \right) \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right) + \frac{\hbar}{2} \omega_q \sigma_z \quad . \quad (2)$$

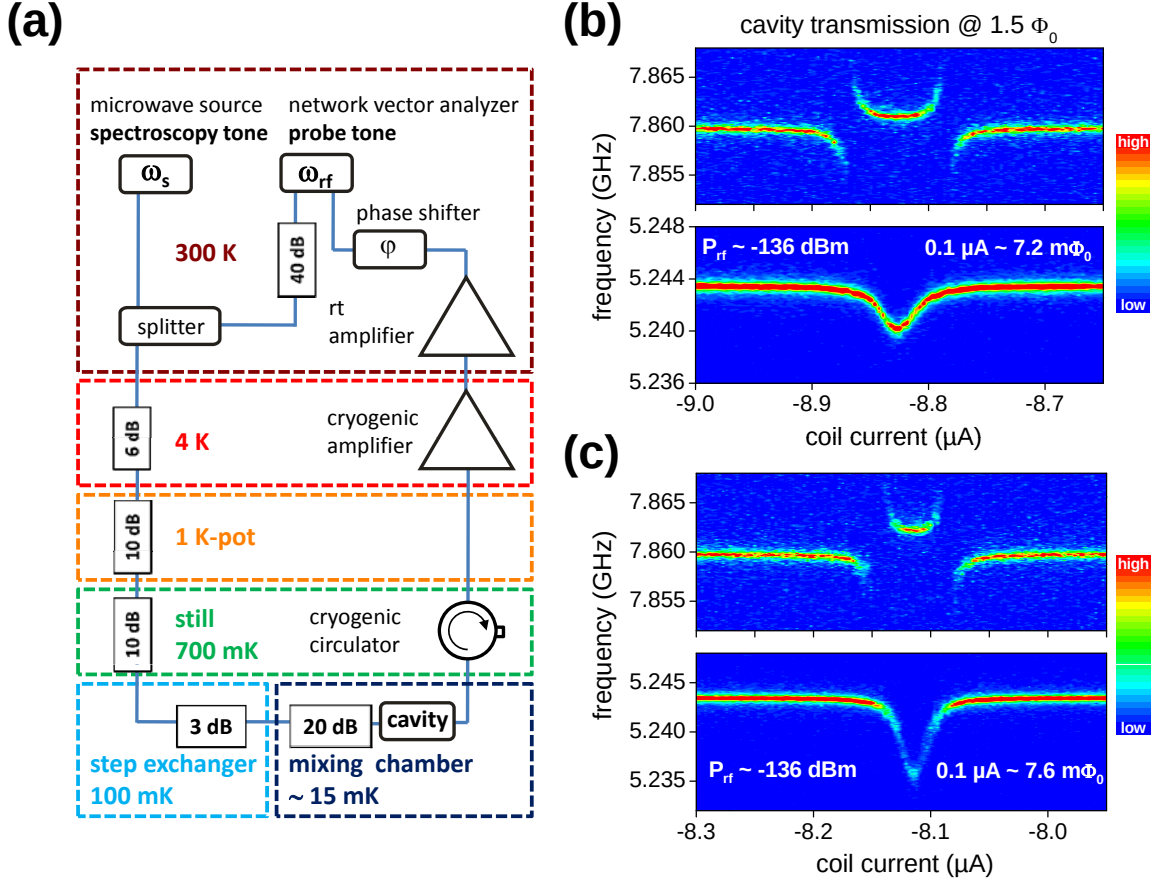


Figure 2: (a) Schematic of the measurement setup. The highly attenuated input line is thermalized at different temperature stages inside the cryostat. A weak probe tone ω_{rf} is used to measure the transmission through the cavity. Using a second microwave source, a spectroscopy tone ω_s is applied through the same input port as the probe tone ω_{rf} is used to excite the qubit. At the output port, a cryogenic circulator acting as an isolator prevents noise from entering our experiment. (b) and (c) show transmission spectra of our cavity as a function of the externally applied field bias. The top panels show avoided crossings at flux values where $\omega_q = \omega_r$. In the lower panels, qubit and resonator are detuned. However, the two systems still interact through a second-order term in the dispersive Hamiltonian leading to a flux-dependent shift of ω_r .

Therefore, the cavity frequency ω_r is shifted by an amount $\pm g^2/\delta$ (ac-Zeeman shift) depending on the state of the qubit. This flux-dependent shift of the cavity frequency is shown in the lower panels of Fig. 2(b) and (c).

The qubit parameters Δ and $\varepsilon(\Phi)$ were obtained in a two-tone spectroscopy experiment [3]. With the qubit in the ground state and for a constant flux bias, we fix the probe tone $\tilde{\omega}_r = \omega_r - g^2/\delta$ at maximum transmission of the first harmonic mode. A second microwave tone, the spectroscopy tone ω_s , is then used to excite the qubit. The spectroscopy power P_s has to be much larger than the probe power P_{rf} , as ω_s is applied off-resonantly to the cavity. When $\omega_s = \omega_q$ and for a large amplitude drive, the qubit will be saturated and the population in the ground and excited state will approach 1/2. This will lead to a shift of the cavity frequency by g^2/δ and thus, to a phase shift and a decrease in magnitude at the fixed probe frequency. With this technique, ω_q can be determined by sweeping both, ω_s and Φ . Figure 3(a) shows a two-tone spectroscopy performed on one of the inductively coupled qubits. Both, the transition frequency at the qubit's degeneracy point $\Delta/\hbar \sim 2\pi \times 5.81$ GHz and $2I_p\Phi_0/\hbar \sim 2\pi \times 1722$ GHz

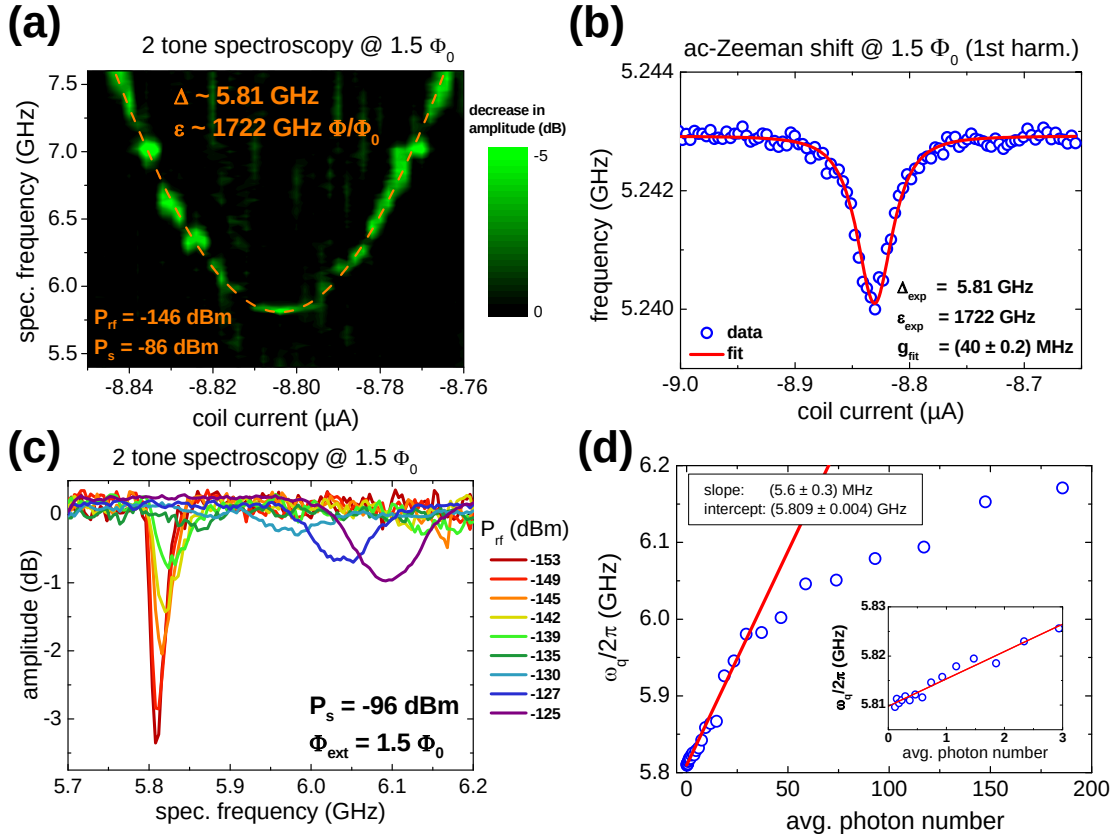


Figure 3: (a) Two-tone spectroscopy performed on one of the SC flux qubits. The qubit parameters can be fitted to the measured spectrum using the relation $\omega_q = \sqrt{\Delta^2 + \epsilon^2(\Phi)} / \hbar$. (b) Using the qubit parameters from the two-tone spectroscopy experiment, the flux-dependent ac-Zeeman shift of the cavity frequency can be fitted. The fit procedure yields a coupling rate of $g/2\pi \sim 40$ MHz in very good agreement with the observed vacuum-Rabi splitting. (c) ac-Zeeman shift of ω_q depending on probe power P_{rf} . When the average photon number $\bar{n} = \langle \hat{a}^\dagger \hat{a} \rangle$ is increased, the qubit peak shifts in frequency and becomes power broadened. (d) Dip minima of (c) plotted versus average photon number $\bar{n}$. From the coupling g the qubit ac-Zeeman shift per photon $2g^2/\delta$ can be calculated. For low photon numbers, the qubit ac-Zeeman shift is linear.

can be obtained by fitting the spectrum. In Fig. 3(b), the experimentally determined qubit parameters are used to fit the flux-dependent ac-Zeeman shift of the cavity frequency. Thus, the coupling $g/2\pi \sim 40$ MHz can be determined. The fitted coupling is in good agreement to the observed vacuum-Rabi splitting. Knowing the coupling g we estimated a mutual inductance $M_{q,c} \sim 5.3$ pH between qubit and resonator using the relation $g = \hbar^{-1} M_{q,c} I_p I_c$, where I_p denotes the persistent current and I_c the cavity vacuum current.

Equation (2) can be rewritten in order to highlight the effect on the qubit

$$\hat{H} \approx \hbar \omega_r \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right) + \frac{\hbar}{2} \left(\omega_q + \frac{2g^2}{\delta} \hat{a}^\dagger \hat{a} + \frac{g^2}{\delta} \right) \sigma_z \quad . \quad (3)$$

The qubit transition frequency ω_q is modified by a photon number dependent ac-Zeeman shift $2g^2/\delta \cdot \hat{a}^\dagger \hat{a}$ and by a Lamb shift g^2/δ , which originates in the coupling to the vacuum fluctuations. The average photon number $\bar{n} = \langle \hat{a}^\dagger \hat{a} \rangle$ can be increased by increasing the probe power $P_{rf} = \hbar \omega_r \kappa \cdot \bar{n}$. Figure 3(c) shows the ac-Zeeman shift of ω_q as a function of P_{rf} using two-tone spectroscopy. For larger drive amplitudes, the qubit dip becomes power broadened and changes from a Lorentzian to a Gaussian line shape [3]. In Fig. 3(d) the position of the dip

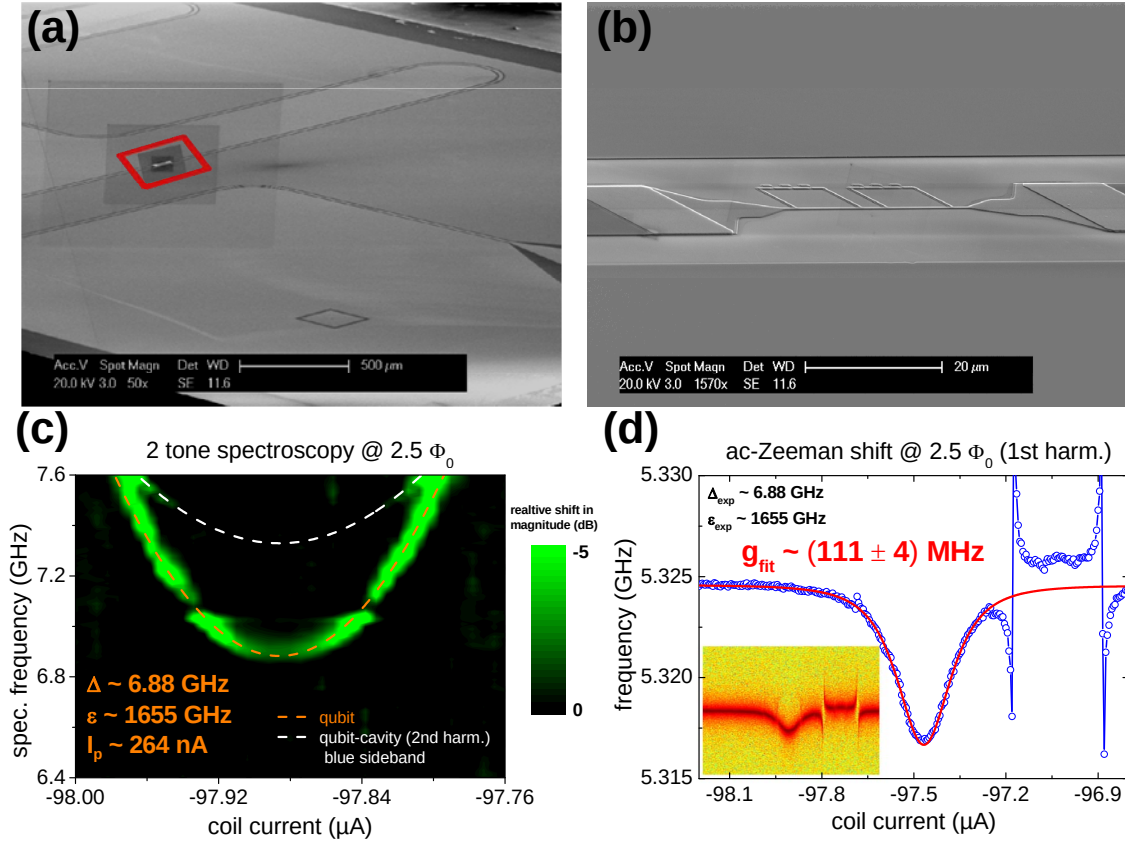


Figure 4: (a) SEM image of a section of a CPW resonator. The red box marks the region where two flux qubits are attached to the central conductor. (b) Magnified view of (a). The kinetic inductance of the narrow constriction enhances the coupling between the qubits and the resonator. (c) Two-tone spectroscopy of one of the galvanically coupled flux qubits. The orange dashed line is a fit to the measured spectrum, the white dashed line indicates a qubit-cavity blue sideband. (d) ac-Zeeman shift of the cavity's first harmonic mode. Fitting the coupling yields $g/2\pi \sim 111 \text{ MHz}$ using the equation $\tilde{\omega}_r = \omega_r - \tilde{g}^2/\delta$. It is important to note, that $\tilde{g} = g \sin \theta$ is a flux-dependent quantity with $\theta = \arctan[\Delta/\epsilon(\Phi)]$, taking into account the different mixing of the cavity and qubit eigenstates depending on the flux value. At the qubits degeneracy point, $\sin \theta = 1$.

minima measured in (c) are plotted versus the average photon number. Because g and δ are known, the shift per cavity photon $2g^2/\delta$ can be calculated. For low photon numbers, the qubit ac-Zeeman shift is linear and intercepts the vertical axis at the qubits bare transition frequency in very good agreement with the spectroscopic measurements shown in Fig. 3(a). Thus, this measurement gives an *in-situ* calibration for the average photon number in the cavity.

Strong coupling limit with galvanically coupled flux qubits

In order to further increase the coupling g between flux qubit and resonator we fabricated samples, where the flux qubits are coupled galvanically to the CPW resonator. The central conductor of the cavity is interrupted at a position where the current standing wave for the first harmonic mode has its maximum. Then, an Al strip narrowing down from $20 \mu\text{m}$ down to a 500 nm wide constriction is fabricated together with two qubits. The shared large kinetic inductance of the narrow Al constriction enhances the coupling. Figure 4(a) shows a SEM image of a section of the resonator, the red box marks the place where the qubit is fabricated. In Fig. 4(b) a magnified view of the two galvanically coupled flux qubits is shown. We per-

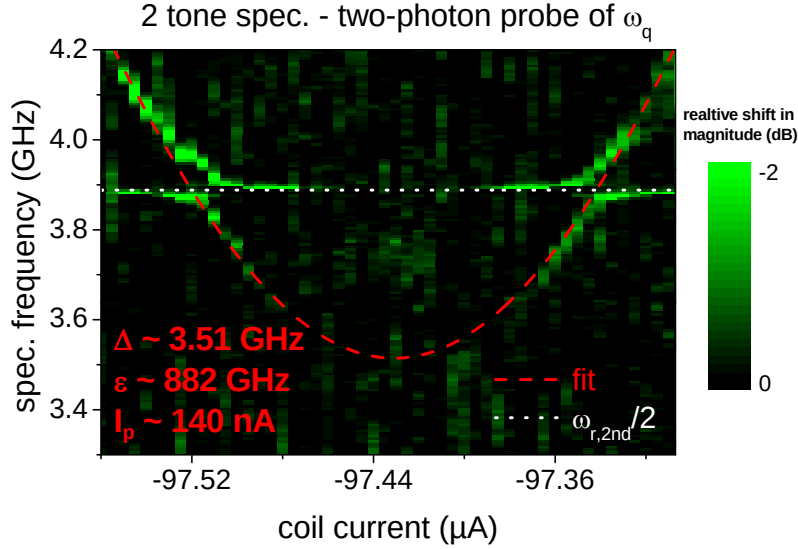


Figure 5: Spectroscopy data obtained from probing the qubit with a drive $2\omega_s = \omega_q$. The matrix element for two-photon driving is proportional to $\sin^2 \theta \cos \theta$ and therefore vanishes at the degeneracy point. The cavity as a harmonic oscillator can not be driven with two photons. The anticrossings result from the strong coupling of the qubit to the second cavity mode. From the anticrossings the coupling g can be measured independently.

formed spectroscopy experiments on this system as explained in the previous section. Figure 4(c) shows the measured data for one of the qubits. The orange dashed line is a fit to the measured spectrum, the white dashed line indicates one of the qubit-cavity blue sideband transitions [4] that can be excited near the anticrossings. The blue sideband can be excited using two drive photons when the relation $2\omega_s = \omega_q + \omega_r$ is fulfilled. With $\Delta/\hbar \sim 2\pi \times 6.88$ GHz and $2I_p\Phi_0/\hbar \sim 2\pi \times 1655$ GHz we fitted the cavity ac-Zeeman shift shown in Fig. 4(d) and obtained a coupling of $g/2\pi \sim 111$ MHz. The inset shows a color plot of the measured data at a flux bias of $\sim 2.5\Phi_0$. The other qubit has a transition frequency at its degeneracy point of $\Delta/\hbar \sim 2\pi \times 2.17$ GHz and, consequently, we see an anticrossing at the measured cavity mode. We also performed spectroscopy on the qubits using a two-photon spectroscopy drive $2\omega_s = \omega_q$. Figure 5 shows the measured spectrum. As the matrix element for two-photon transitions is proportional to $\sin^2 \theta \cos \theta$ with $\theta = \arctan[\Delta/\varepsilon(\Phi)]$, the spectroscopic signal vanishes at the qubit degeneracy point. The two anticrossings result from the strong coupling to the second cavity mode. The coupling g can thus be measured directly without populating the cavity. As a harmonic oscillator, the cavity can not be driven directly with two photons. The measured coupling g is in good agreement with previous measurements.

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Gradiometric flux qubit with tunable gap

M. J. Schwarz, T. Niemczyk, G. Wild, F. Deppe, A. Marx, R. Gross¹

In contrast to a classical bit, which always occupies one of the two distinct states "0" or "1", a so-called qubit (quantum bit) can also exist in a quantum superposition of these two states. When it was shown 15 years ago that on a possible quantum computer composed of thousands of coupled qubits certain algorithms such as prime factorization can be executed exponentially faster with increasing input size than on a classical computer, the new field of quantum information processing was born. Since then, quantum information processing has been a very active field and qubits have been realized in various physical systems including quantum optical systems, nuclear magnetic resonance systems, quantum dots and superconducting circuits based on Josephson junctions. The latter have several advantages, e.g. concerning the well-known scalability and tunability inherent to solid-state circuits. Moreover, these micrometer-sized systems behave as artificial two-level atoms and therefore offer the possibility to investigate fundamental quantum phenomena on a macroscopic scale. Different types of superconducting qubits can be distinguished, depending on the physical variable, which contains the information. At the WMI, we focus on the realization of flux qubits, where the quantum information is encoded in the magnetic flux generated by a persistent current in a superconducting loop containing three Josephson junctions. In particular, we study a gradiometric design which provides an *in-situ* controllably energy gap without being detuned from the point of optimal phase coherence.

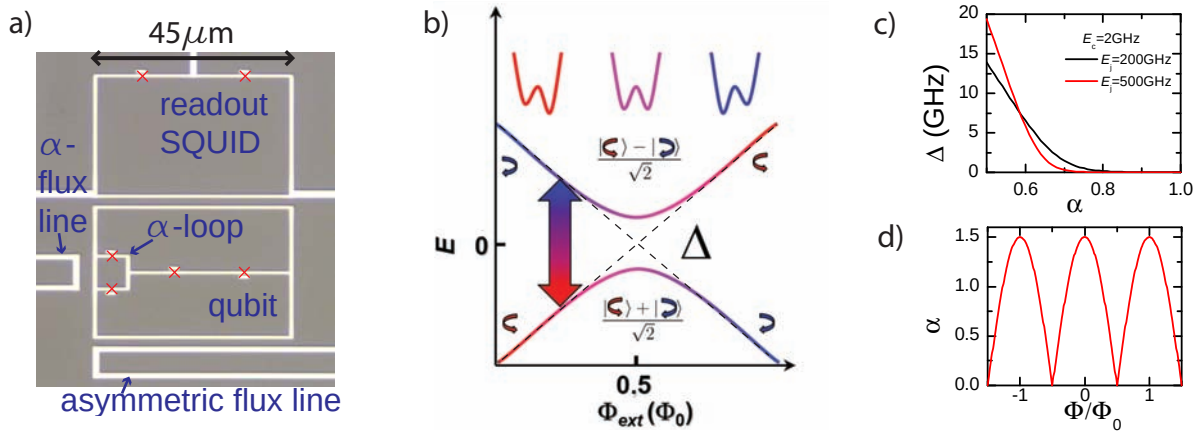


Figure 1: (a) Microscope image of the fabricated samples, showing the readout SQUID, the gradiometric eight-shaped qubit with the α -loop and the two flux lines (junction positions marked by red crosses). (b) Energy diagram of a flux qubit as a function of external magnetic flux Φ_{ext} . Black dashed lines: classical states; colored lines: quantum mechanical states due to anti-crossing. The qubit transition frequency - corresponding to the arrow - is dependent on the flux bias and also on the qubit gap Δ . (c) Numerical simulations show that the qubit gap Δ is strongly dependent on α . (d) The effective value of α of the dc SQUID loop can be manipulated over a wide range via an applied magnetic flux Φ .

The three-junction flux qubit, which has been studied at the WMI during the last years, consists of a superconducting loop interrupted by three nm-sized Josephson junctions [1, 2]. Two of these Josephson junctions have the same area $A \approx 0.02 \mu\text{m}^2$ and, hence, the same critical current I_c . The third Josephson junction is smaller by a factor $\alpha \approx 0.6-0.8$, which is crucial for the formation of a quantum two-level system. In its gradiometric version, the flux qubit consists of two galvanically coupled loops with the Josephson junctions placed on the shared line. Furthermore, the smaller α -Josephson junction is replaced by a dc SQUID-loop with two Josephson junctions, acting as an effective Josephson junction [cf. Fig. 1(a)]. The qubit energy diagram as

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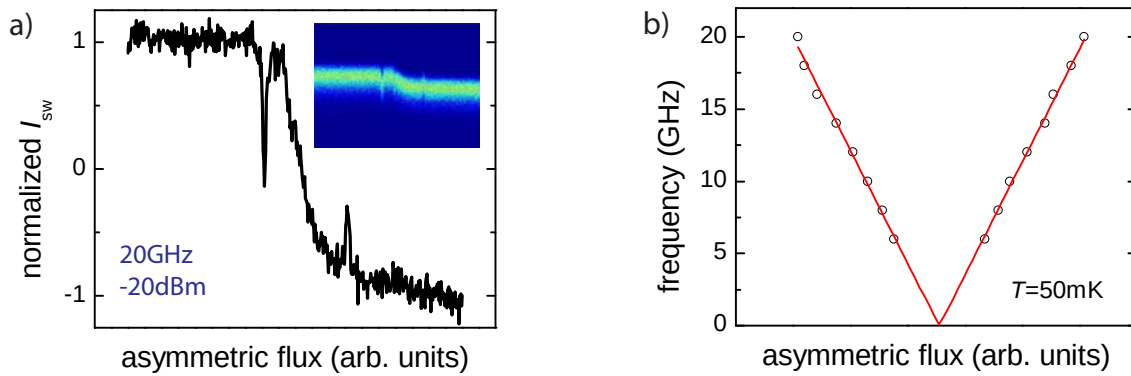


Figure 2: (a) Normalized switching current I_{SW} of the readout dc SQUID plotted versus magnetic flux bias of the qubit, showing a qubit step and next to it a dip and a peak, respectively, due to the absorption of a microwave signal ($\nu=20\text{GHz}$). The inset shows the switching current distribution in a color coded image. (b) Qubit transition frequency (circles) plotted versus magnetic flux. The red line is a numerical fit indicating a vanishing gap, as expected for no additional flux applied to the α -loop.

a function of applied magnetic flux is depicted in Fig. 1(b). At a flux bias of half a flux quantum an anti-crossing of the two classical branches (black dashed lines) corresponding to clockwise and counterclockwise circulating currents results in a quantum mechanical superposition of the two states (colored lines). By irradiating a microwave signal of a certain frequency the qubit can be excited from the ground to the excited state. The qubit state can be detected with a dc SQUID via the flux signals of clockwise and counter-clockwise circulating currents in the loop [3].

In experiments, it is often favorable to change the qubit transition frequency, e.g., in order to switch on or off the coupling of the qubit to a microwave resonator. According to Fig. 1(b), this can be done by changing the applied magnetic flux. However, keeping the magnetic flux constant at the point of the anti-crossing provides an important advantage: Since the energy of the qubit is stationary with respect to variations of the magnetic flux at this point, minimal flux noise and therefore maximal phase coherence of the qubit is obtained [3]. Nevertheless, the transition frequency can be varied for a fixed magnetic flux by changing the distance between the two branches, i.e., tuning the energy gap Δ of the qubit. This consideration was the starting point for a new flux qubit design with an *in-situ* control of the qubit gap [4]. The qubit gap Δ strongly depends on the parameter α [cf. Fig. 1(c)], which can be varied *in-situ* when replacing the smaller α -junction with a dc SQUID loop, consisting of two junctions with a suitable critical current. The overall critical current of the α -loop then depends on the magnetic flux applied to this loop [cf. Fig. 1(d)] and can be manipulated via an additional flux line. In order not to change the flux bias of the qubit, this α -flux line must not affect the qubit loop. Therefore, a gradiometric design of the qubit is used, making it insensitive to any flux that is applied symmetrically to both loops of the now eight-shaped qubit [cf. Fig. 1(a)]. Consequently, another asymmetric flux line is necessary to adjust the flux bias of the qubit.

Using electron beam lithography, two-angle shadow evaporation and Al technology, we have fabricated such a device together with a readout SQUID. The Josephson junctions of the α -loop are designed to be smaller by a factor 0.75 than the other qubit Josephson junctions, which gives a maximum value of $\alpha=1.5$ for zero flux applied to this loop. In a dilution refrigerator at a temperature of about 30 mK we have investigated the characteristics of the qubit via the readout SQUID. When we vary the magnetic flux in the qubit by changing the current through the asymmetric flux line, the switching current distribution of the readout SQUID shows a clear step. The assumption, that this feature originates from the switching of the qubit's persistent

current direction, is confirmed by spectroscopic measurements. For this, a microwave signal is irradiated onto the sample and yields a characteristic peak and dip, respectively, next to the step, as depicted in Fig. 2(a). By varying the microwave frequency the energy diagram can be measured [cf. Fig. 2(b)]. For zero flux applied to the α -loop we see no gap, which is consistent with the geometric dimensions of the junctions. Without any flux in the α -loop, the maximal value $\alpha=1.5$, yielding no gap, is expected.

In summary, we have fabricated a gradiometric flux qubit with a tunable α -loop. Spectroscopy measurements show that the qubit is operating as expected. In a next step we will use the α -flux line to deliberately vary the gap of the qubit. When a sufficient tunability of the qubit has been achieved, an implementation of this qubit into other projects at the WMI – such as the circuit QED experiments with a qubit coupled to a microwave resonator – can be pursued.

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Macroscopic quantum properties of Josephson junctions with ferromagnetic interlayer

G. Wild, A. Marx, C. Probst, R. Gross¹

The interplay between magnetism and superconductivity has attracted strong interest since many years. Recently, the possible application of Josephson junctions with ferromagnetic interlayer in quantum circuits has been proposed. An appropriate choice of the ferromagnetic interlayer thickness may lead to the appearance of a π phase shift across such junction, making them suitable as π phase shifters in superconducting quantum circuits. Concerning this application, it is important to clarify whether or not magnetic excitations in the ferromagnetic interlayer interact with the macroscopic quantum behavior of the Josephson junction, thereby causing additional noise and decoherence.

The geometry of our Josephson junctions is sketched in Fig. 1. Two superconducting niobium electrodes (red) are coupled through a ferromagnetic $\text{Pd}_{0.82}\text{Ni}_{0.18}$ interlayer (yellow) in a planar geometry. An additional Al-AlO_x layer (black) increases the junction resistance, thereby reducing resistive damping. A SiO_2 layer around the mesa structure isolates the top and bottom niobium electrodes outside the junction area.

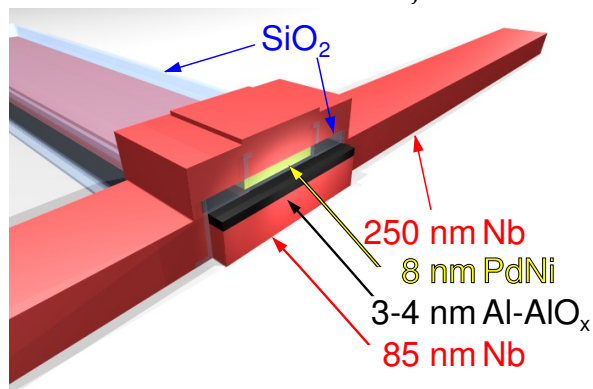


Figure 1: Sketch of a planar superconductor/insulator/ferromagnetic metal/superconductor Josephson junction used in this study. The planar geometry allows for transport measurements via a four-probe technique. The layer structure from bottom to top is 85 nm niobium, a 3-4 nm Al-AlO_x barrier layer, 8 nm PdNi and 250 nm niobium. For clarity the bottom electrode is shortened.

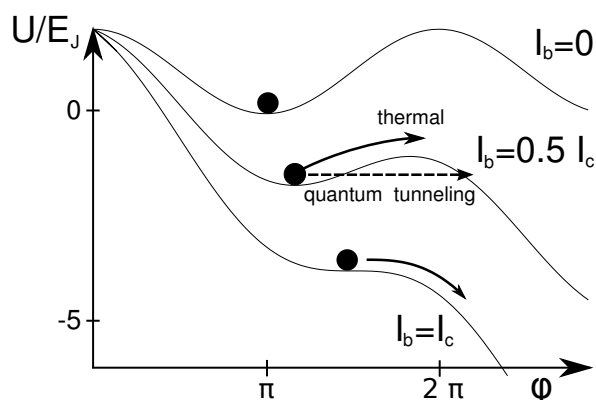


Figure 2: Tilted washboard potential. The dynamics of a Josephson junction is analog to a phase-particle in a tilted washboard potential $U(\varphi)$. The particle localized in a local minimum of the potential represents a Josephson junction in the zero voltage state. When the phase particle escapes the potential well it starts running down the potential landscape due to its finite inertial mass. According to the second Josephson equation this describes a Josephson junction in the voltage state. The tilt of the potential is proportional to the junction bias current I_b .

However, up to now it is not clear whether a ferromagnetic interlayer in a Josephson junction induces noise and thus renders these junctions useless for quantum circuits. To shed some light on this issue we study the escape of the Josephson junctions out of the zero-voltage into the voltage state, a process which is governed by quantum tunneling at low enough temperatures. In this way, the question whether the quantum properties of the junctions are affected by magnetic excitations in the ferromagnetic interlayer can be addressed by comparing the experimentally determined crossover temperature from thermally activated to quantum tunneling escape with the theoretical prediction.

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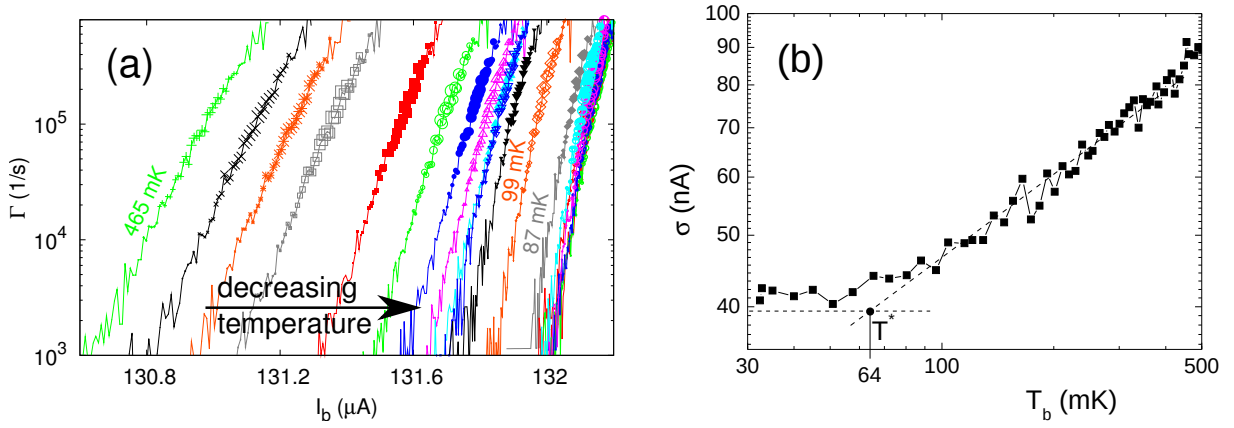


Figure 3: (a) Measured escape rates of a $20 \times 20 \mu\text{m}^2$ Josephson junction plotted versus the bias current I_b at different temperatures. (b) Width of the switching current histograms σ plotted versus bath temperature T_b for the same junction. Each width σ is extracted from a separate set of measurements. The symbol size in (a) is proportional to the number of events representing the point. The histogram width saturates below a temperature $T^* = 64 \text{ mK}$ in agreement with the theoretical expectation.

The dynamics of a π -Josephson junction is analog to a phase particle in a tilted washboard potential $U(\varphi)$. At zero bias current I_b , we have $U(\varphi) = E_J[1 - \cos(\varphi + \pi)]$ as shown in Fig. 2. Here, E_J is the Josephson coupling energy and φ the phase difference across the junction. Evidently, a π -Josephson junction has a minimum of the potential energy for $\varphi = \pi$. At finite I_b , the washboard potential is tilted by the bias current applied to the junction. In our experiment, starting from zero current where the phase particle is trapped in a potential well, the bias current is slowly ramped up and hence the tilt of the potential is steadily increased. By increasing the tilt, the height and width of the potential barrier preventing the escape of the phase particle is decreased and thus the probability for thermally activated or tunnel escape out of the well continuously increased. At the specific switching current I_{sw} the particle escapes the well and starts to run freely. According to the second Josephson relation a continuously increasing phase corresponds to a voltage across the junction, which can be easily detected. This measurement is repeated about a thousand times and a histogram of the switching current I_{sw} is acquired. This histogram allows to determine the escape probability $\Gamma(I_b)$ as a function of the bias current I_b using an algorithm introduced by Fulton and Dunkelberger [1].

Figure 3(a) shows a histogram for a $20 \times 20 \mu\text{m}^2$ π -Josephson junction with a ferromagnetic interlayer at different bath temperatures T_b . At high temperatures the escape is dominated by thermal activation described by an escape probability [2]

$$\Gamma_t(T) = \frac{\omega_p}{2\pi} \exp^{-\frac{U}{k_B T}} \quad (1)$$

with the plasma frequency ω_p , the Boltzmann constant k_B and the activation energy U . The saturation at low temperatures may be either caused by external noise or internal noise originating in the ferromagnetic interlayer or by reaching the quantum limit for escape. To clarify this issue we compare the theoretically expected crossover temperature into the quantum limit T_{th}^* to the saturation temperature T_{exp}^* observed in the experiment.

In Fig. 3(b) we show the histogram width σ (standard deviation of the switching currents) versus bath temperature T_b for a different set of data obtained for the same junction. Here, a large value corresponds to a broad histogram and hence to a line with small slope in Fig. 3(a). For the data shown in Fig. 3(b) we use a linear approximation to extract the saturation temperature of about

$$T_{\text{exp}}^* = 64 \text{ mK} \quad . \quad (2)$$

The theoretical prediction given in Ref. [3]

$$T^* = \frac{\hbar\omega_p}{2\pi k_B} \left(\sqrt{1 + \left(\frac{1}{2Q}\right)^2} - \frac{1}{2Q} \right) = \frac{\hbar\omega_p}{2\pi k_B} \left(1 - \frac{1}{2Q} + \frac{1}{8Q^2} - \dots \right). \quad (3)$$

depends on the plasma frequency ω_p of the junction and its quality factor Q , which both depend on the applied bias current. The plasma frequency for zero bias current ω_{p0} has been determined by microwave spectroscopy experiments at mK-temperature to $\omega_{p0}/2\pi=22.4$ GHz. The quality factor for zero bias current Q_0 can be determined from the hysteresis in the current-voltage characteristics and is obtained to $Q_0 \approx 6$. Both values have to be scaled by $\alpha=[1 - I_b^2/I_c^2]^{1/4}\approx 0.4$ to take into account the bias current dependence. Inserting these values into Eq. (3) results in the theoretically expected crossover temperature

$$T_{th}^* = 53 \text{ mK} \quad . \quad (4)$$

Comparing the values of Eq. (2) and Eq. (4), one observes a small discrepancy between the theoretically predicted and the experimentally observed crossover temperatures T_{th}^* and T_{exp}^* . However, in the evaluation of the data shown in Fig. 3(b) we have not considered the bias current dependence of the plasma frequency since the width of the histograms at higher temperature are determined at lower bias current I_b and therefore at a higher plasma frequency $\omega_p=\alpha\omega_{p0}$. Taking this effect into account the experimentally determined crossover temperature is slightly decreased and we find a good agreement of the measured saturation temperature T_{exp}^* and the theoretically expected crossover temperature T_{th}^* . This gives strong evidence that we indeed observe a quantum tunneling dominated escape out of the zero voltage state at low temperatures. From this observation we also can conclude that there is a negligible effect of low-lying magnetic excitations in the ferromagnetic interlayer on the junction dynamics. If such excitation would be present and significant for the junction dynamics, the observation of a markedly increased T_{exp}^* would have been expected.

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Spatially resolved spin mechanics

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Multifunctional material systems such as multiferroics incorporate several ferroic phases and thus show new or unconventional interactions. In particular, ferromagnetic/ferroelectric hybrid structures enable an electric field-control of magnetization orientation. In the last years, we have pursued the concept illustrated in Fig. 1(a) to its limits: A piezoelectric material will deform if an electric field is applied [Fig. 1(b) and Fig. 1(c)]. In a ferromagnet rigidly attached to the piezoelectric, this mechanical deformation will induce strain. Because of magnetoelastic coupling, however, mechanical stresses alter the magnetic anisotropy in the ferromagnet. Thus, an electro-mechanical deformation of the piezoelectric actuator/ferromagnet hybrid allows to control the *magnetic* properties in-situ, solely by applying *electric* fields [Fig. 1(b) and Fig. 1(c)]. We recently demonstrated that this *spin mechanics* concept indeed works in various hybrid systems [1–5]. Figure 1(d) exemplarily shows that the application of an electric voltage to the piezoelectric actuator allows to generate an easy (for positive voltage polarity) or a hard magnetic axis (for negative voltage polarity) in the ferromagnetic Ni film attached to it.

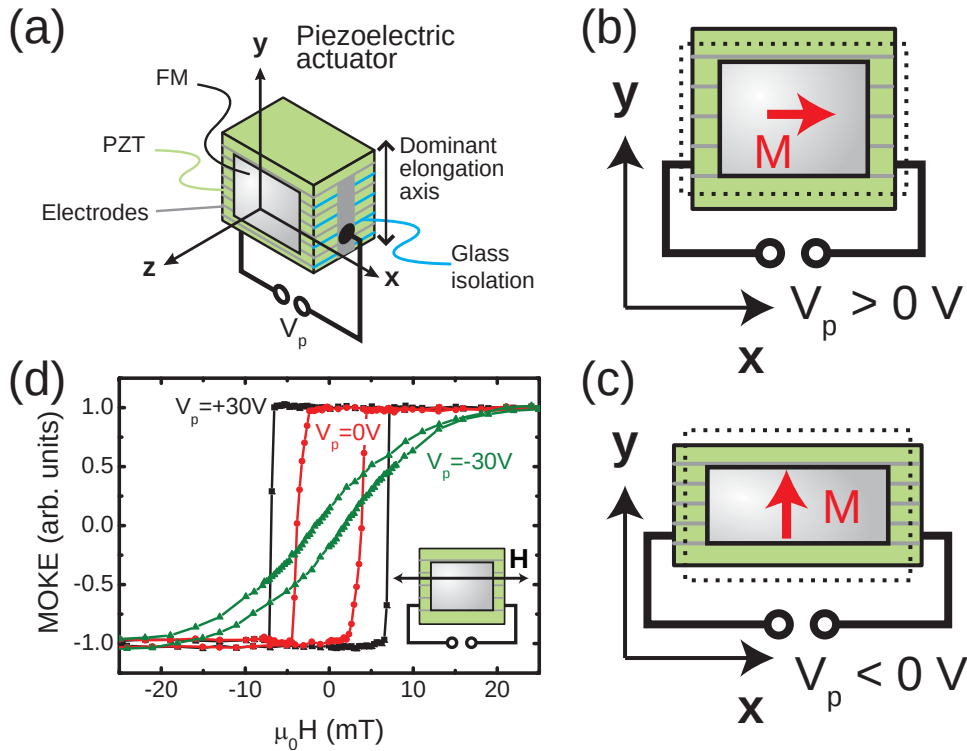


Figure 1: (a) Schematic illustration of the *spin mechanics* hybrid structure concept. A ferromagnetic film is rigidly attached to a piezoelectric actuator. (b), (c) The deformation of the actuator upon applying a voltage $V_p > 0$ V and $V_p < 0$ V, respectively, induces strain in the ferromagnet. The dotted contours indicate the actuator at $V_p = 0$ V and the red arrow depicts the magnetization orientation and thus the direction of the magnetic easy axis. (d) MOKE $M(H)$ hysteresis loops of a Ni thin film on actuator at different applied voltages.

To date, our experiments relied on an integral measurement of the magnetization vector, either by SQUID magnetometry [5], angle-resolved magneto-transport [6], or by magneto-optical Kerr effect (MOKE). However, the spin mechanics approach should also allow to locally control the magnetization orientation, e.g. via the generation of local mechanical strain. We here

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discuss a first important step towards local spin mechanics, using spatially resolved magneto-optical Kerr effect as a means to study the magnetization texture.

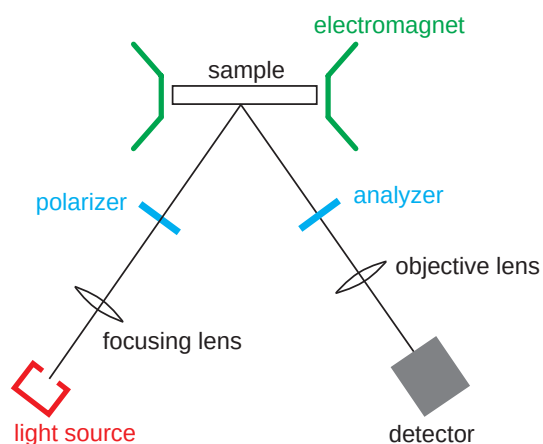


Figure 2: Schematic diagram of the MOKE setup for spatially resolved magnetization measurements.

Figure 3 depicts typical spatially resolved MOKE images. To obtain sufficient signal to noise ratio, we used the difference image procedure, i.e. we recorded a Kerr image at a given magnetic field H_{meas} and a given voltage V_p , and subtracted a reference image recorded at the same V_p , but at a magnetic field H_{sat} large enough to saturate the magnetic film. In this way, only magnetic contrast will prevail, while in particular strain induced birefringence can not contribute to the signal. To be more exact, in the data presented in Fig. 3, we first magnetically saturated the Ni film at $\mu_0 H_{\text{sat}} = -40$ mT with an easy direction along the magnetic field axis ($V_{p,\text{prep}} = +30$ V), then applied the measurement field $H_{\text{meas}} = +8$ mT, swept the voltage to the value of interest V_p and recorded the first image. Subsequently, the magnetic field was swept back to H_{sat} without changing V_p , and the reference image was recorded. If this procedure is applied using $V_p = V_{p,\text{prep}} = +30$ V, one obtains the difference image shown in Fig. 3(a). The Ni film with an area $A \approx 3 \text{ mm}^2$ appears as a homogeneous, grayish patch. This shows that for this combination of H_{meas} and V_p magnetization reversal or domain nucleation has not yet started. In contrast, if one repeats the experiment using the same H_{meas} but $V_p = 0$ V [Fig. 3(b)], a local magnetization reversal becomes apparent in the form of whitish stripes in the difference image. A more negative V_p leads to larger reversed domains [Fig. 3(c)] and finally to a full, all-electrically triggered magnetization reversal [Fig. 3(d)].

Figure 2 schematically depicts how we have extended our conventional longitudinal MOKE setup to enable spatially resolved magnetization measurements. A high power LED in the visible regime (center frequency $\lambda = 627$ nm) served as a light source, and the Kerr signal was recorded with a CCD-camera with a pixel size of approx. $10 \mu\text{m} \times 10 \mu\text{m}$. While this setup has a rather low spatial resolution in the range of several micrometers (depending on the lenses used, cf. Fig. 2), it is comparatively flexible and cheap, and allows to quantitatively compare the integral (MOKE) approach used so far with spatially resolved measurements.

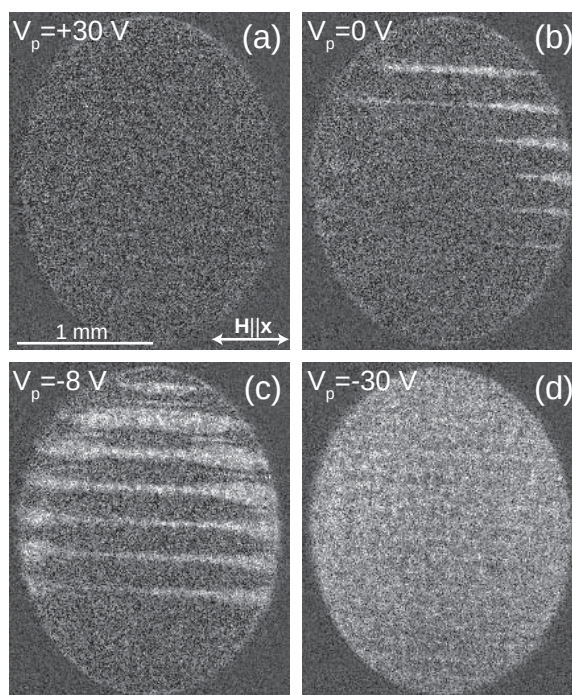


Figure 3: Magnetization switching in a nickel/piezoelectric actuator hybrid system upon changing the applied voltage V_p at an external magnetic field $\mu_0 H = +8$ mT. The difference images shown were taken at (a) $V_p = +30$ V, (b) $V_p = 0$ V, (c) $V_p = -8$ V, and $V_p = -30$ V, respectively.

These results show that a local electric-field control of magnetization is indeed possible using the spin mechanics approach. The local strain is stemming from a spatially inhomogeneous deformation of the piezoelectric actuator, which consists of PZT stacks sandwiched between conducting electrodes. The elastic properties of the electrodes and the PZT layers differ, so that a mechanical deformation of the actuator will always result in a spatially modulated strain. As evident from Fig. 3, such a local strain enables local magnetization control. Clearly, further experiments are needed to clarify down to which length scales this mechanical control of magnetism is possible.

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Giant changes of magnetic anisotropy in $\text{Sr}_2\text{CrReO}_6$ thin films on BaTiO_3

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Composite or hybrid material systems consisting of ferromagnetic (FM) and ferroelectric (FE) compounds have attracted increasing interest over recent years. They provide strong magnetoelectric coupling, enabling an electric field-control of the FM magnetization or a magnetic field-control of the FE polarization, making them promising for new storage devices [1]. The FM double perovskite $\text{Sr}_2\text{CrReO}_6$ (SCRO) with a Curie temperature of 635 K [2] well above room temperature shows a spin polarization of 86% according to band structure calculations [3] and a giant anisotropic magnetostriction [4]. In the past, we successfully optimized the epitaxial growth of high-quality SCRO thin films on single crystalline SrTiO_3 substrates [5]. Here, we study SCRO thin films on FE BaTiO_3 substrates to investigate the magnetic and transport properties under different strain conditions [6]. BaTiO_3 undergoes several structural phase transitions upon temperature variation. It becomes FE below 393 K and its lattice structure changes from cubic to tetragonal. Within this FE state, the lattice symmetry is further reduced to orthorhombic below 278 K and finally to rhombohedral below 183 K. Its dielectric constant, spontaneous FE polarization, and lattice constants change abruptly at these phase transition temperatures.

The SCRO thin films were grown using pulsed laser deposition in an oxygen atmosphere of 6.6×10^{-4} mbar at a substrate temperature of 700° C. They were characterized by high resolution x-ray diffraction (Fig. 1). In the tetragonal phase of BaTiO_3 , the ω -2 θ scan (Fig. 1(a)) reveals no crystalline parasitic phases in the film, but shows a splitting of the BaTiO_3 substrate reflection due to the presence of different FE domains (*a*-domains: $\text{BaTiO}_3(200/020)$ and *c*-domains: $\text{BaTiO}_3(002)$). A more detailed picture of the structural properties and the domain configuration is obtained from reciprocal space maps around the SCRO(004) and SCRO(116) reflections (Fig. 1(b,c)). It shows that the SCRO film grows *c*-axis oriented and partially relaxed with lattice parameters of $a_{\text{SCRO}}=5.614$ Å and $c_{\text{SCRO}}=7.88$ Å. Moreover, the presence of differently oriented *a*-domains ($\text{BaTiO}_3(200)$, $\text{BaTiO}_3(020)$, $\text{BaTiO}_3(301)$, and $\text{BaTiO}_3(031)$) is clearly observed.

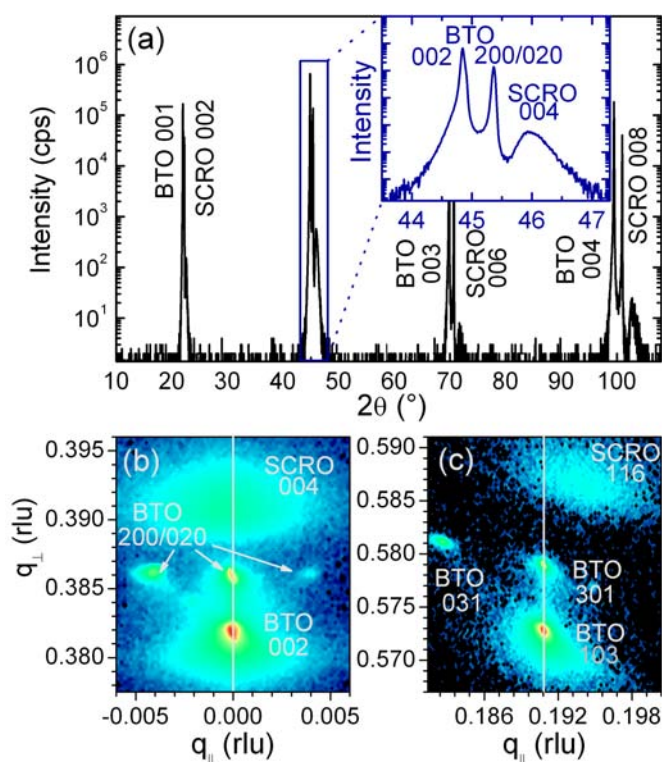


Figure 1: X-ray diffraction from a 81 nm thin SCRO film at 310 K. (a) ω -2 θ scan. (b,c) reciprocal space maps around the SCRO(004) and (116) reflections. Different reflections from the FE domains of the BaTiO_3 (BTO) substrate are clearly visible.

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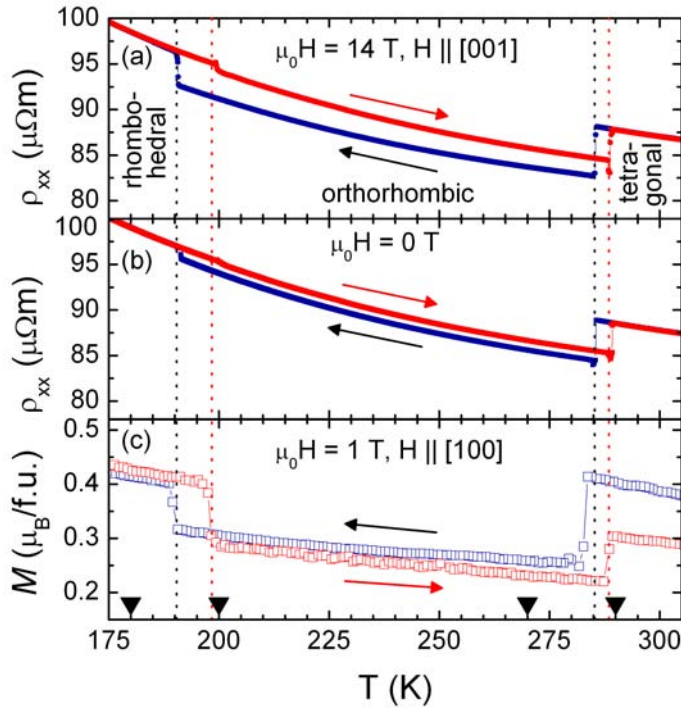


Figure 2: Temperature dependence of (a) the longitudinal resistivity ρ_{xx} at $\mu_0 H = 14 \text{ T}$ and (b) 0 T as well as (c) the magnetization M at 1 T . Both ρ_{xx} and M show jumps at the BaTiO₃ phase transition temperatures (dotted lines). The black triangles in (c) indicate the temperatures at which the $M(H)$ measurements in Fig. 3 were carried out.

thermal hysteresis due to the first order phase transitions of the BaTiO₃ substrate. Furthermore, the resistivity in the rhombohedral and tetragonal phase is also quite independent of the applied magnetic field $\mu_0 H$. Only the values in the orthorhombic phase depend strongly on the sweep direction and the magnetic field. Such a hysteresis can be attributed to different volume fractions of a - and c -domains in the orthorhombic phase depending on whether the previous phase was rhombohedral or tetragonal [8]. The resistivity jumps evident from Fig. 2 are in the range of several percent (up to 6.5%). A pure geometric origin, namely due to a change in the length and the cross-sectional area of the current path can be ruled out as the structural changes yield an upper bound for the resistance changes of about 1% for both transitions. Anisotropic magnetoresistance effects also should be small as the magnetization is essentially saturated at an external field of 14 T. On the other hand, it is well known that double perovskites like SCRO are very sensitive towards distortions of the crystal and the corresponding change in the overlap of the orbitals [9]. We therefore suggest that the observed resistance jumps are related to strain-induced changes in the orbital configuration of SCRO.

This should also affect the magnetic properties of the SCRO thin film. Figure 3(a) shows the magnetization M versus external magnetic field H , oriented along BaTiO₃[100] for four different temperatures: 290 K, 270 K, 200 K, and 180 K. All $M(H)$ loops look similar, except for the absolute value of the magnetization at high fields ($|\mu_0 H| > 4 \text{ T}$). In the tetragonal (crosses in Fig. 3) and the rhombohedral phase (full circles) of BaTiO₃, M is nearly identical, whereas in the orthorhombic phase (open circles and triangles) a reduction is observed. This indicates a reduced saturation magnetization which might be due to the highly twinned BaTiO₃ crystal in that phase.

Whenever the BaTiO₃ substrate undergoes a structural phase transition, the associated change of the lattice parameters should affect the magnetic and electronic properties of the SCRO thin film clamped to its surface [7]. The longitudinal resistivity ρ_{xx} , measured in an external field of $\mu_0 H = 14 \text{ T}$ orthogonal to the film plane (Fig. 2(a)), and in zero field (Fig. 2(b)) shows a qualitatively similar behavior. Upon cooling the sample from 300 K (black lines), the resistivity increases slightly until it suddenly drops at 285 K, i.e. at the temperature at which BaTiO₃ becomes orthorhombic. Between 285 K and 191 K, the resistivity increases again continuously until it jumps to higher values at 191 K, where BaTiO₃ becomes rhombohedral. Further cooling leads to a steadily increasing resistivity.

The red curves in Fig. 2, measured while warming up, reproduce the behavior described above with a

In the following, we discuss in more detail the field dependence of the magnetization in the different BaTiO₃ phases for three different orientations of the external magnetic field: ip ($H \parallel [100]$), ip45 ($H \parallel [110]$), and oop ($H \parallel [001]$) (Fig. 3(b)). The temperatures for the field sweeps were chosen slightly above and below the phase transition from tetragonal to orthorhombic (290 K and 270 K) and from orthorhombic to rhombohedral (200 K and 180 K) as indicated by the black triangles in Fig. 2. First, we consider the evolution of the in-plane anisotropy. In this case, the external magnetic field is applied in the film plane with two orientations: ip (full circles) and ip45 (open circles). In the tetragonal phase of BaTiO₃, at 290 K (Fig. 3(c)), the two hysteresis loops are very similar. Both show a coercive field of around 0.92 T, and the magnetizations at 7 T are nearly identical ($0.6 \mu_B/\text{f.u.}$). This suggests a negligible in-plane magnetic anisotropy. In the orthorhombic phase of BaTiO₃, at 270 K and 200 K (Fig. 3(d,e)), the situation is completely different. The coercivities of the ip and ip45 loops differ by more than 1 T. In particular, the hysteresis loops at 200 K reveal a coercive field of 0.87 T for the ip orientation of the external field and a much larger value of 2.3 T for the ip45 orientation. Thus, a tremendous in-plane magnetic anisotropy is present. Upon cooling into the rhombohedral phase of BaTiO₃ (Fig. 3(f)), the situation changes again. The coercive fields and the magnetizations at 7 T for both in-plane hystereses (ip and ip45) as well as the oop loop (open triangles) are nearly identical. In other words, the magnetic behavior appears isotropic with no evidence of contributions from shape or crystalline anisotropy. This is remarkable as it suggests that giant strain-induced anisotropies of more than 1 Tesla are effective in the SCRO film, compensating demagnetization.

In summary, we have shown that the strain associated with different crystalline phases of the FE BaTiO₃ substrate induces qualitative changes both in the resistivity and in the magnetic anisotropy of FM epitaxial Sr₂CrReO₆ thin films. Abrupt jumps of up to 6.5% in the resistivity, as well as giant changes in the coercive field of more than 1.2 T were observed as a function of temperature. These observations can be consistently understood considering orbital ordering and the strong electronic correlations in double perovskite ferromagnets [6].

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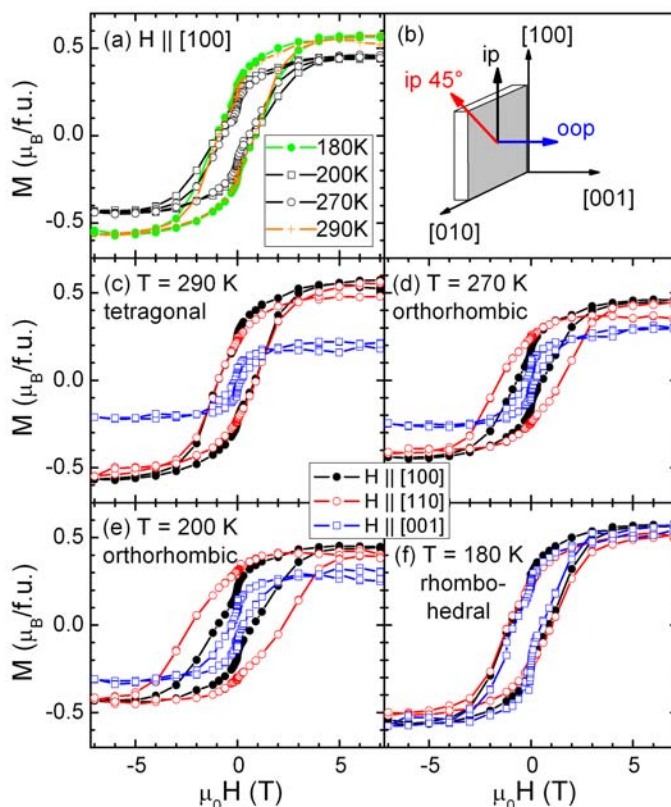


Figure 3: Magnetization M versus external magnetic field H . (a) Hysteresis loops at different temperatures. (b) Illustration of the different orientations of the external field. Panels (c)–(f) show hysteresis loops at specific temperatures for different orientations of the external magnetic field.

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Spin mechanics with surface acoustic waves

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Magnetoelastic interaction phenomena can be used to control the static magnetization state in ferroelectric/ferromagnetic hybrids [1–4]. In these hybrids, the mechanical deformation of the ferroelectric constituent is controlled with an electric voltage. Due to magnetoelastic coupling, the magnetization state of the ferromagnet is connected to the mechanical strain state of the hybrid. In last year's annual report we discussed this *spin mechanics* (voltage-strain-magnetization) control scheme in the DC limit in detail [5].

Transferring this spin mechanics approach to finite frequencies would allow to mechanically drive dynamic magnetization processes - possibly even ferromagnetic resonance. However, the piezoelectric actuator / ferromagnetic thin film hybrids we have used to date can not be operated at frequencies above ≈ 100 kHz due to intrinsic limitations of the actuator. Therefore, another means to generate mechanical deformation at MHz frequencies and above is required. For this purpose, surface acoustic waves (SAWs) are ideal, as they allow to generate nanoscale mechanical motion at frequencies up to several gigahertz. We therefore have fabricated surface acoustic wave delay lines consisting of two interdigital transducers (IDTs) at the two ends of a SAW propagation path [cf. Fig. 1(a)]. These delay lines allow to generate and detect SAWs all electrically. The IDTs were prepared using optical lithography and aluminum lift-off on y-cut z-propagating lithium niobate SAW-grade substrates. The fundamental center frequency f_0 of the SAW depends on the periodicity p of the fingers,

$$f_0 = \frac{v}{\lambda} = \frac{v}{p} \quad (1)$$

with the velocity of sound v which is about 3500 m/s in lithium niobate.

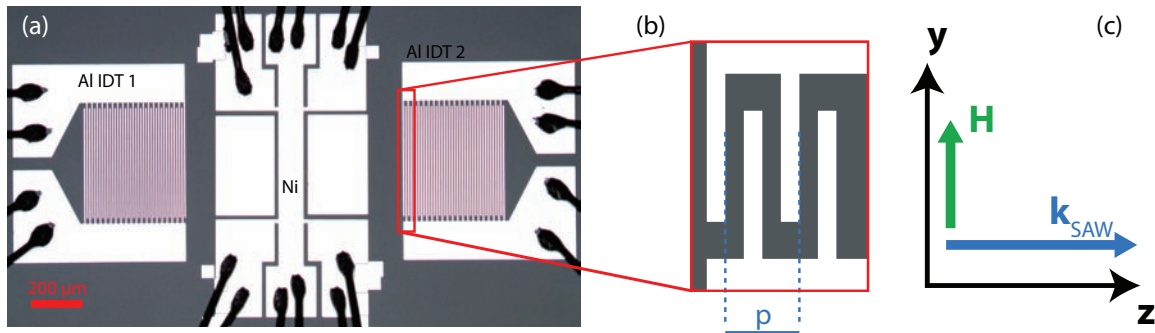


Figure 1: (a) Micrograph of an actual sample showing the aluminum IDT pair and the Ni Hall bar (both contacted for measurement). (b) Schematic closeup of 2 finger pairs. (c) The external magnetic field $\mathbf{H}$ is applied orthogonal to the SAW wave vector $\mathbf{k}_{\text{SAW}}$.

To study the interaction of the SAW with a ferromagnetic thin film in the spirit of spin mechanics, we deposited a 50 nm thick, polycrystalline nickel film in the SAW propagation path. The Ni film is patterned into a Hall bar shape to allow for DC magnetoresistance measurements. RF contacts to the IDTs were established using high-frequency co-axial cables,

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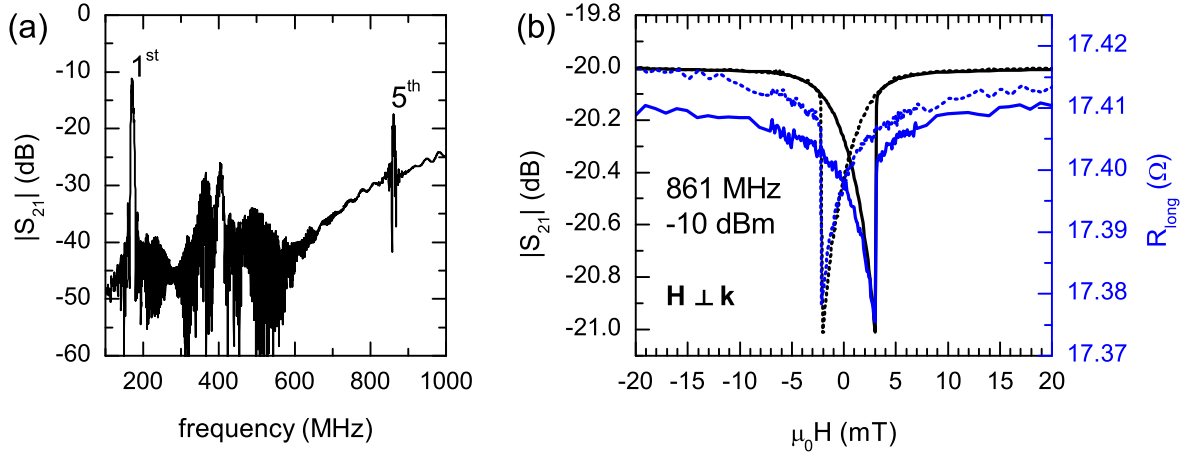


Figure 2: (a) RF power transmission as a function of frequency for a SAW delay line with a fundamental frequency of 172.2 MHz. (b) 861 MHz RF transmission (black) compared to longitudinal resistance (blue) as a function of the applied magnetic field. The up-sweep is depicted by the solid lines and the down-sweep by the dotted lines.

coplanar waveguides and bond wires. A micrograph of a typical SAW / ferromagnet hybrid is shown in Fig. 1(a). The schematic closeup in Fig. 1(b) illustrates the IDT design, with the definition of the periodicity p which is equivalent to the SAW wavelength λ for operation at f_0 . Using a vector network analyzer (VNA) we determined the RF power transmitted through the SAW delay line as a function of frequency at zero external magnetic field. This transmission – more precisely the magnitude of the scattering parameter S_{21} – is shown in Fig. 2. Within the frequency span shown in Fig. 2, two transmission maxima (at 172.2 MHz and 861 MHz, respectively) can be identified and attributed to SAWs. These maxima correspond to the SAWs traveling at the fundamental frequency $f_0=172.2$ MHz and at the fifth harmonic $5f_0$. In IDTs with a metalization ratio of 0.5 (finger width equals finger spacing), the fifth harmonic frequency is the first harmonic frequency which can be excited [6]. The transmission maxima observed between the SAW transmission peaks are attributed to bulk acoustic waves.

To investigate the interaction between the magnetization of the ferromagnet and the SAW, the sample shown in Fig. 1(a) was mounted in an electromagnet in such a fashion that the external magnetic field $\mathbf{H}$ was orthogonal to the SAW wave vector $\mathbf{k}_{\text{SAW}}$ (cf. Fig. 1(c)). The experiments discussed here were carried out at room temperature, simultaneously recording the SAW transmission $|S_{21}|$ at $5f_0=861$ MHz⁴ and the DC magnetoresistance R_{long} as a function of the magnetic field magnitude $\mu_0 H$. Figure 2 shows R_{long} (blue) and $|S_{21}|$ (black) thus obtained. Hereby, the solid lines depict the data recorded for increasing the external magnetic field (upsweep) and the dotted lines the data recorded for decreasing the external magnetic field (downsweep). The abrupt change in R_{long} indicates the coercive field $H_c \approx 2.5$ mT⁵. Clearly, the qualitative evolution of the magnetotransmission $|S_{21}|$ with H mimics R_{long} , although the relative change in transmission is much larger than the relative change in resistance. Hence we conclude that the SAW propagation indeed is sensitive to the magnetization state in the Ni film. The details of the interaction mechanism are currently under investigation. One possible explanation is a magnetic field dependent change of the mechanical hardness of the Ni film, the so-called ΔE effect [7].

⁴More precisely, we averaged a sweep of $|S_{21}|$ with a center frequency of 861 MHz and a sweep span of 6 MHz, corresponding to the full width at half maximum of the SAW transmission peak.

⁵The fact that the switching fields for up-sweep and down-sweep occur at slightly different magnetic field values is attributed to hysteresis in the electromagnet.

In summary, we have demonstrated that SAWs on lithium niobate substrates interact - at ambient conditions - with polycrystalline nickel thin films deposited in their propagation path. The high-frequency interaction is dependent on the static magnetization of the Ni film, as evident from the correlation between DC magnetotransport and RF magnetotransmission. This opens intriguing new perspectives for spin mechanics at high frequencies.

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Raman scattering study of the charge density wave phase in rare-earth tri-tellurides at high pressure

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The rare-earth tri-telluride ($R\text{Te}_3$) compounds are quasi two-dimensional metals, which undergo an electronically driven charge density wave (CDW) phase transition already at high temperatures - some of them even above room temperature. Electronic ordering and phase transitions in the $R\text{Te}_3$ compounds became a very active field of research, as the situation resembles the one in the cuprates, where high temperature superconductivity may emerge from charge ordering [1, 2]. Recently, superconductivity with $T_c < 3$ K was indeed found in TbTe_3 at high pressure [3] right next to the CDW phase.

The CDW phase transition is driven by an instability in the electron system, which is coupled to the crystal lattice via the electron phonon interaction. Electronic instabilities are at the origin of phenomena as diverse as the formation of spin and charge density waves or superconductivity. Besides determining the ground state of the quantum system in which they occur, they also fundamentally affect its excitation spectrum. In particular, they induce new types of collective behavior, the investigation of which can be used to identify the kind of electronic order involved. In the CDW state, on which we focus here, a gap opens up in the single particle spectrum, and two new collective modes, associated with the oscillations of the amplitude and of the phase of the CDW appear [4].

The $R\text{Te}_3$ compounds host an unidirectional, incommensurate CDW already well above room temperature for all R elements lighter than Dy [5], while in the heavy rare-earth tri-tellurides (i.e., $R = \{\text{Tm}, \text{Er}, \text{Ho}, \text{Dy}\}$) the corresponding transition temperature, $T_{\text{CDW}1}$, lies below 300 K and decreases with increasing R mass. In the latter systems, a further transition to a bidirectional CDW state occurs at $T_{\text{CDW}2}$, ranging from 180 K for TmTe_3 to 50 K for DyTe_3 [5]. The drastic change in transition temperatures with the size of the R ion or externally applied pressure on a given material [6] is accompanied by a similarly large change in the properties of the CDW itself. In particular, the CDW gap of $R\text{Te}_3$ progressively collapses when the lattice constant is reduced, which, in turn, induces a transfer of spectral weight into the metallic component of the excitation spectrum [7], the latter resulting from the fact that the Fermi surface in these materials is only partially gapped by the formation of the CDW. The response of this residual metallic component completely screens all optically active modes (including the collective CDW phase excitation) and makes their observation by infrared absorption methods impossible.

Raman scattering, on the other hand, is an excellent technique to study the influence of chemical and applied pressure on the lattice excitations in the lighter rare-earth tri-tellurides [7]. The measurements at applied pressure are performed in a home-made diamond anvil cell, the

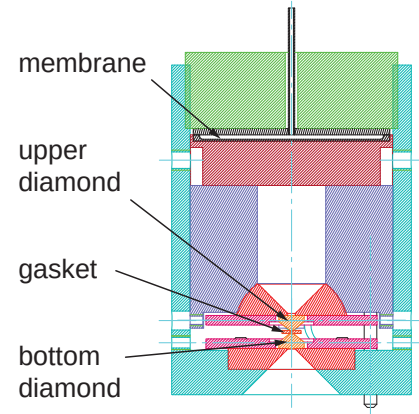


Figure 1: Schematic drawing of the diamond anvil cell.

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cross section of which is shown in Figure 1. The high pressure is generated by means of a metal membrane which applies a force to the upper diamond of the cell while the bottom diamond is fixed. In the volume enclosed by the tips of the diamonds and a metal gasket we reached pressures as high as 18 GPa. The accessible temperatures range from 2 K up to 350 K. The pressure is determined by ruby fluorescence technique [8] and as a pressure transmission medium either nitrogen or helium can be used.

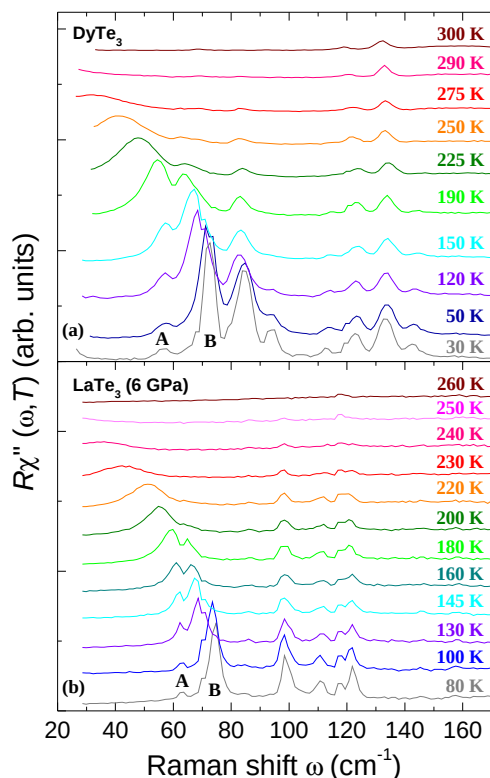


Figure 2: Temperature dependence of the Raman scattering spectra as a function of temperature on (a) DyTe₃ ($T_{CDW1}=307$ K, $T_{CDW2}=49$ K [5]) and (b) LaTe₃ at 6 GPa [9].

Upon destroying the CDW state with increasing temperature, the sharp B mode first softens, gets progressively broader and loses spectral intensity in favor of the A feature (Fig. 2(a) and Fig. 3(a). At T_{tr} of approximately 170 K (160 K) for DyTe₃ (LaTe₃ at 6 GPa), the two modes roughly share the same amount of spectral intensity (Fig. 2 and Fig. 3(a). Upon approaching T_{CDW1} the energy of the B mode becomes constant, while its intensity drops above T_{tr} and vanishes at T_{CDW1} , as does that of the A mode, whose resonance frequency saturates at 23 cm^{-1} [Fig. 3(a) and Fig. 4(a)]. In the low temperature spectra of DyTe₃ an additional mode [labeled D in Fig. 3(b) and

Figure 2 shows a comparison of Raman scattering spectra as a function of temperature on (a) DyTe₃, with a transition temperature of $T_{CDW1}=307$ K and (b) LaTe₃ at 6 GPa [9]. In LaTe₃ at 6 GPa the lattice is compressed to a lattice constant between that of DyTe₃ and HoTe₃, and T_{CDW1} close to 260 K [6, 10]. The general trend in temperature for both sets of data is quite similar, suggesting that by compressing the lattice hydrostatically, (as for LaTe₃ at 6 GPa), one can recover the properties and response of chemically compressed RTe₃ (i.e., through substitution of the R element). This confirms earlier findings at 300 K as a function of pressure [7]. At low temperatures and deep in the CDW state, we observe well distinct and rather sharp modes. Above 80 cm^{-1} the modes, previously ascribed to the Raman active phonons with A_{1g} , and A_1 and B_1 symmetry for the undistorted (pseudotetragonal) and distorted phase respectively [7], lose spectral weight with increasing temperature, while their widths marginally change as a function of temperature. For $\omega \leq 80\text{ cm}^{-1}$ and at low temperatures there is a weak peak close to 60 cm^{-1} and a sharp one around 70 cm^{-1} (labels A and B in Fig. 2), in agreement with the findings of Ref. [11]. Their temperature dependences are specifically emphasized for DyTe₃ in Fig. 3(a) [9].

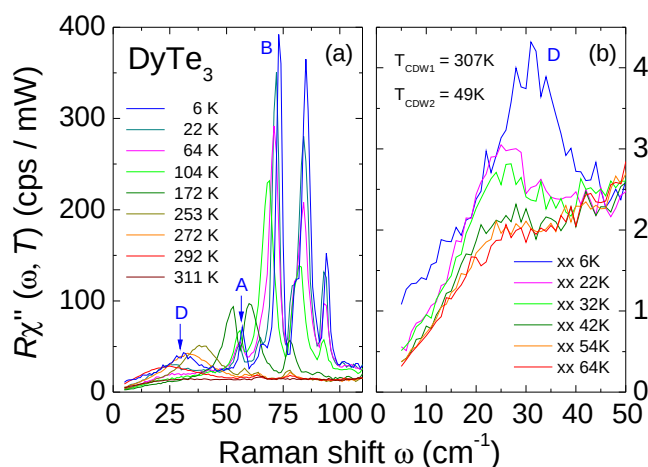


Figure 3: (a) Temperature dependence of the amplitude modes (A and B) associated with the unidirectional CDW. (b) Temperature dependence of the bidirectional CDW amplitude mode D [9].

Fig. 4(a)] in the range below 50 cm^{-1} is found, which disappears upon increasing the temperature above $T_{\text{CDW}2}$. Interestingly, its energy at $T_{\text{CDW}2}$ saturates at the same value (23 cm^{-1}) as the one of the A mode at $T_{\text{CDW}1}$, which we interpret as being due to an impurity scattering rate of this order of magnitude in our sample [12]. As a consequence, a quantitative analysis of the low energy spectral range in terms of Lorentz oscillators is not possible. Yet, from the temperature dependence observed in Fig. 3(b), we can safely conclude that this mode is the collective amplitude mode of the bidirectional CDW state.

Figure 4 shows the temperature dependences of the resonance frequencies and integrated intensities of the modes evolving with the CDW. For a quantitative analysis we propose the following scenario. At $T_{\text{CDW}1}$ the system undergoes a transition into one of the two predicted unidirectional CDW states [7]. As the temperature is lowered, the minimum on the free energy surface, corresponding to the first unidirectional CDW, moves towards smaller values of the wavenumber q , until it reaches a (saddle-) point at a temperature close to T_{tr} where it becomes more favorable for the system to settle into the second calculated soft mode. So we observe that the unidirectional CDW transition is a two-fold transition.

This situation can be quantitatively described by a model involving two temperature-dependent modes coupled to a phonon with a temperature-independent frequency. The fitting results shown in Fig. 4(a) and Fig. 4(b) were obtained by assuming that the two modes have resonance frequencies proportional to the respective condensate densities ($n_c(T)$, thin dotted lines in panel (a),

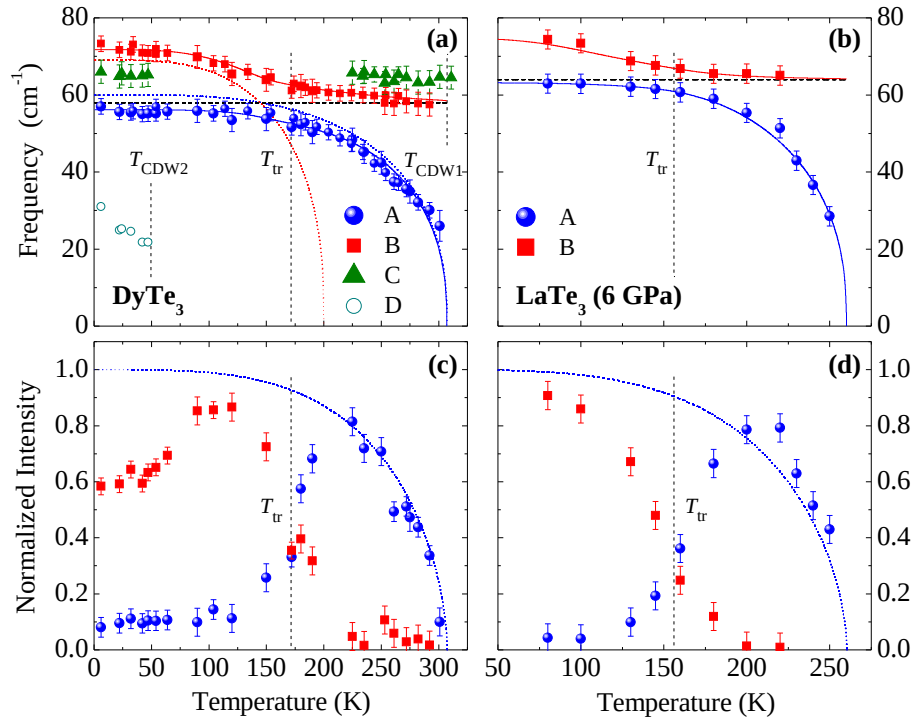


Figure 4: Temperature dependence of the resonance frequencies [(a) and (b)] and of the normalized integrated intensities [(c) and (d)] of the modes in DyTe₃. Explanation see text. [9]

and that they interact with the phonon at about 59 cm^{-1} (63 cm^{-1}) for DyTe₃ (LaTe₃) [dashed line in Fig. 4(a) and Fig. 4(b)] with a coupling constant of $\sim 5 \text{ cm}^{-1}$ ($\sim 4 \text{ cm}^{-1}$). Because of the interaction of this phonon with the amplitude mode we see an anti-crossing behavior. Surprisingly $n_c(T)$ fits the frequency dependence of the data much better than $\sqrt{n_c}$, which would be expected [4] for a CDW amplitude mode. The model also implies a transfer of spectral intensity between A and B: Above T_{tr} mode A is dominant, while below mode B prevails. At T_{tr} both modes have the same integrated intensity [Fig. 4(c) and Fig. 4(d)]. Close to $T_{\text{CDW}1}$ there is good agreement between the integrated intensity of feature A and the prediction for the BCS order parameter, i.e. $I_A(T) \sim \Delta(T)$. Mode C is a phonon, which exists already above $T_{\text{CDW}1}$ and survives the transition without displaying any temperature dependence.

Mode C is too weak to be visible on the scale of Fig. 2 and Fig. 3. Another peculiarity is the loss of spectral intensity of the B mode [Fig. 4(c)] at low temperatures ($T \lesssim 50$ K), which balances the increase of intensity observed below $T_{\text{CDW}2}$ for the collective mode associated with the bidirectional CDW [Fig. 3(b)]. The frequency positions of the bidirectional CDW amplitude mode are labeled as D in Fig. 4(a).

In summary, we have clearly identified the collective amplitude modes of both the uni- and the bidirectional CDW ground state in $R\text{Te}_3$. Upon entering the unidirectional CDW state with decreasing temperature, we have observed a transfer of spectral intensity between two excitations, giving clear evidence for a two-step transition at $T_{\text{CDW}1}$ and close to T_{tr} . This cascade of transitions is rather unconventional but yields a consistent picture of the evolution of the collective excitations in $R\text{Te}_3$ over the whole range of existence of the CDW.

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Band- and momentum-dependent electron dynamics in $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

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The discovery of superconductivity in materials containing iron was a big surprise [1]. After the observation of transition temperatures of more than 30 K in the so-called iron pnictides in the beginning of 2008 an enthusiastic search for materials with higher transition temperatures began. This search resulted in materials with critical temperatures exceeding 50 K and additionally in a large variety of different compounds having iron layers. The compounds with the currently highest transition temperatures of 56 K [2] are the so-called 1111-compounds crystallizing in the ZrCuSiAs -type structure. These materials contain fluorine making the crystal growth and handling complicated. Another class of materials are the so-called 122-compounds crystallizing in the ThCr_2Si_2 -type structure [Fig. 1(a)]. These compounds have maximal transition temperatures below 40 K [3] but contain neither fluorine nor oxygen, and large single crystals can be grown.

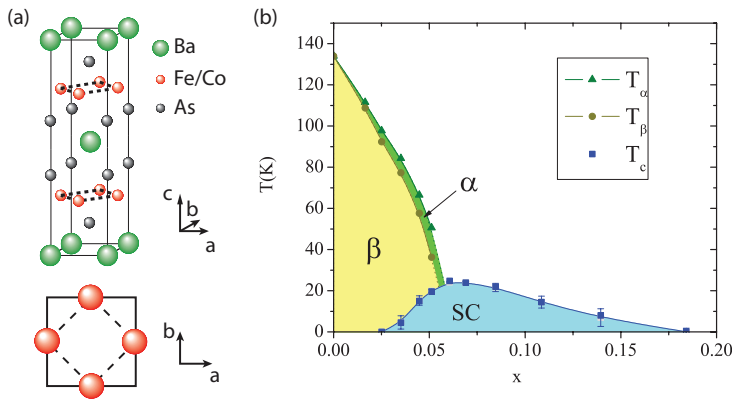


Figure 1: (a) Unit cell of BaFe_2As_2 and the FeAs plane. The relevant Fe cell is smaller by a factor of 2 and rotated by 45° . (b) Phase diagram of $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ (from [4]). The compound shows a tetragonal to orthorhombic transition (T_α) which is completely suppressed for optimal doping and a transition to a magnetically ordered phase with SDW order (T_β , yellow). The superconducting region is indicated in blue (from [5]).

The iron pnictides exhibit a transition to an antiferromagnetic ground state with spin-density-wave (SDW) order and a structural tetragonal to orthorhombic transition upon lowering the temperature [Fig. 1(b)]. Superconductivity can be achieved by applying pressure [6] or by doping. To dope the compound, an atom in the unit cell of the parent compound has to be replaced by another element having less (hole doping [3]), more (electron doping [4]) or even an equal number of electrons [7]. Additionally to

the occurrence of superconductivity, doping suppresses the structural and magnetic transitions of the compound. However, it is unclear if doping is essential to provide an optimal number of charge carriers or to suppress the structural and/or magnetic transitions [8].

Despite the different crystallographic structures there is general agreement concerning the electronic structure of the iron pnictides. The Brillouin zone (BZ) of the undoped compound consists of two hole-like cylinders at the Γ -point and two electron-like barrels at the M-point [9] having approximately the same cross section (Fig. 2). The Fermi surface (FS) pockets show, at least for low doping levels, nesting properties which are gradually suppressed upon doping. At least one important issue still remains to be solved: the pairing interaction which

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results in such high transition temperatures and, connected to that, the question of the symmetry of the superconducting energy gap. To answer this question Boeri *et al.* performed local-density-approximation calculations for the iron pnictides which predicts weak electron phonon coupling. Using standard Migdal-Eliashberg-theory [10], T_c is predicted to be of order 1 K. Therefore, conventional phonon-mediated *s*-wave superconductivity is unlikely. Inspired by the nesting properties between hole and electron pockets other authors considered interactions based on magnetically mediated pairing resulting in a gap having nodes on one of the FS sheets [11] or in an extended *s*-wave ($s^\pm$ -wave) symmetry of the gap. This gap changes sign between the hole and electron bands but does not have any nodes along the FS [12].

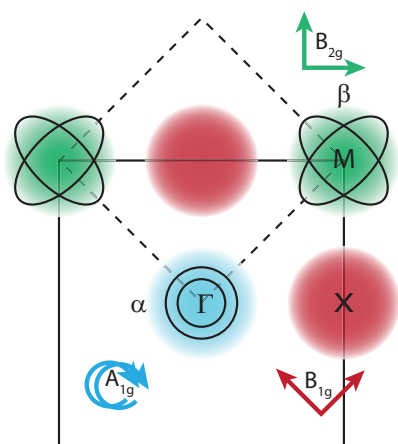


Figure 2: BZ of the iron arsenides and selection rules for a Raman light scattering experiment: By aligning the polarization state of the incoming and outgoing photon properly in the basal plane different region in the BZ can be projected out represented by different symmetries. B_{2g} symmetry (green) and A_{1g} (blue) probe the β and α bands, respectively (from [5]).

axis where no bands cross the Fermi level. In contrast, A_{1g} tests both the central hole and the electron bands but charge backflow effects largely screen the contribution of the electron bands leaving predominantly the hole bands (Fig. 2). With these findings Raman scattering is a very powerful tool for the investigation of the iron pnictides since we can test the electronic properties of the bulk on different bands separately.

For the superior crystal quality we chose the electron-doped superconductor $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$. The Raman spectra of the investigated sample $\text{Ba}(\text{Fe}_{0.939}\text{Co}_{0.061})_2\text{As}_2$ with $T_c=24$ K [4] show a strong symmetry dependence. In B_{1g} symmetry there is no significant difference between the normal- and the superconducting spectra measured at 30 K and 8 K respectively (not shown here). In contrast, there is a clear redistribution of spectral weight in B_{2g} symmetry. The superconducting spectrum shows a very pronounced pair breaking peak at approximately 70 cm^{-1} and a suppression of the low energy spectral weight with respect to the normal state [Fig. 3(b)]. In A_{1g} symmetry we find a suppression of spectral weight at low energy and a broad pair breaking peak at 100 cm^{-1} or $6 k_B T_c$ [Fig. 3(a)]. The peaks at 145 cm^{-1} and 185 cm^{-1} are due to phonons [20]. The superconducting peak in A_{1g} symmetry is less pronounced than in B_{2g} and the higher peak position indicates a larger gap amplitude on the α than on the β bands which is consistent with photoemission results [21]. The insets of Fig. 3(a) and Fig. 3(b) show the slope of the spectra in both symmetries on a log-log scale. The spectral

The experimental side is controversial as well: Angle-resolved-photo-emission-spectroscopy (ARPES) [13] and Andreev spectroscopy measurements [14] were interpreted as evidence of a nodeless gap with *s*- or $s^\pm$ -wave symmetry. While the analysis of inelastic neutron scattering experiments in conjunction with ARPES data detected a $s^\pm$ -wave symmetry of the gap [15], nuclear magnetic resonance [16] and penetration depth data [17] are consistent with nodes in the gap.

We use inelastic light (Raman) scattering to gain insight into electron dynamics and the structure of the gap. In an electronic Raman scattering (ERS) experiment photons are scattered off the electrons, thereby creating electron-hole pairs across the Fermi level (normal state) or breaking Cooper-pairs (superconducting state). The photons we use are in the visible range of the spectrum and have a penetration depth of approximately 30 nm. By the appropriate adjustment of the polarization combinations of the incoming and outgoing photons we can probe different regions in the BZ independently [18]. Since the bands in the pnictides lie at high symmetry points in the BZ B_{2g} symmetry probes mainly the electron bands while B_{1g} probes the principle

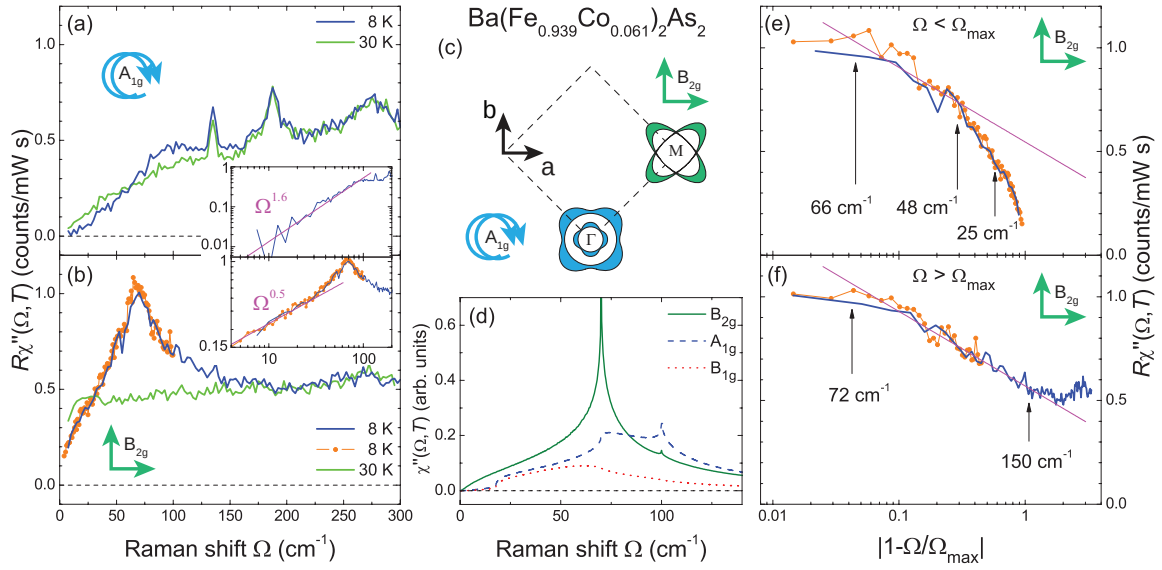


Figure 3: Raman response $R\chi''(\Omega, T)$ of $\text{Ba}(\text{Fe}_{0.939}\text{Co}_{0.061})_2\text{As}_2$ in (a) A_{1g} and (b) B_{2g} symmetry. The full lines correspond to a resolution of 5.0 cm^{-1} while the orange dots a measured with a resolution of 3.6 cm^{-1} . The insets show the power-law behavior of the initial slope of the spectra in the superconducting state. (d) shows the theoretically obtain spectra with the energy gaps mapped in (c). The spectra in A_{1g} and B_{1g} symmetry are multiplied by factors of 0.5 and 10, respectively, for better visibility. (e) and (f) contain spectra in B_{2g} symmetry on a logarithmic scale highlighting the divergence around the peak maximum at $\Omega_{\text{max}} = 69 \text{ cm}^{-1}$. From [5, 19].

intensity down to the lowest measured energies supports the presence of very small if not vanishing minimal superconducting gaps.

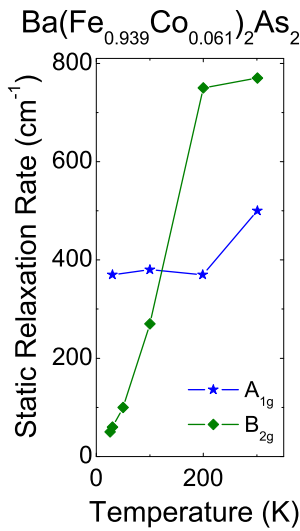


Figure 4: Raman relaxation rates of $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ in B_{2g} symmetry (green) and A_{1g} (blue). The anisotropy of the relaxation rates indicates different relaxations on the α and β bands.

The calculated spectra in Fig. 3(d) are obtained with momentum-dependent energy gaps without sign change having near nodes on the α bands and accidental nodes on the β bands [Fig. 3(c)]. The spectra reproduce the experimental data namely the disappearing response in B_{1g} and the broad maximum with the superconducting peak at 100 cm^{-1} in A_{1g} symmetry. Moreover, the theory predicts the sublinear initial slope in B_{2g} with a very sharp peak at 70 cm^{-1} and a logarithmic divergence. The B_{2g} pair breaking peak is shown in greater detail plotted as $|1 - \Omega/\Omega_{\text{max}}|$ in Fig. 3(e) and Fig. 3(f) on a logarithmic scale using $\Omega_{\text{max}} = 69 \text{ cm}^{-1}$. Here we find a universal linear variation over half a decade and a decade on the low and high energy side of the peak, respectively. The divergence of the peak is cut only by the resolution of the spectrometer.

This indicates the high purity and quality of the investigated sample which is also revealed in the normal state. Here we find qualitatively different relaxation rates on the α and β bands (Fig. 4) [22]. While the relaxation on the α bands is nearly temperature-independent, the relaxation on the β bands exhibits a strong temperature dependence. At low temperature we find very low relaxation rates which is seen by transport data on the same crystal as well [4] and about an order of magnitude larger relaxation rates at high temperatures. These small relaxation rates on the β bands at low temperatures are consistent with the sharp features in the superconducting state.

Thus, with ERS we find a strong momentum dependence in the normal- and superconducting states of $\text{Ba}(\text{Fe}_{0.939}\text{Co}_{0.061})_2\text{As}_2$. In the superconducting state these measurements are consistent with an energy gap having near nodes and accidental nodes on the hole like α - and the electron-like β -bands, respectively. This multigap behavior is in disagreement with ARPES measurements [13], where nodeless superconductivity was found on both bands, and in good agreement with heat transport [23] and penetration depth studies [24]. The discrepancies can originate from surface related problems which are serious in ARPES but more relaxed for bulk sensitive Raman spectra. Another possibility could be that small changes in the electronic structure of the samples are responsible for differences in the gap. This is suggested by our recent measurements but remains to be clarified.

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Specific heat and magnetization measurements on YbRh_2Si_2 at millikelvin temperatures

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YbRh_2Si_2 is a Heavy Fermion compound which shows quite unconventional behavior around a quantum critical point (QCP) at 60 mT. A QCP marks a continuous phase transition at $T=0$ with pronounced deviations from the usual Landau Fermi-liquid state. It can be reached, e.g., by suppressing magnetic order by pressure, including chemical pressure through doping, and in some cases by a magnetic field. YbRh_2Si_2 is such a case where a weak antiferromagnetic phase below 70 mK [1] can be tuned through a QCP by a magnetic field of only 60 mT in the $B \parallel (a, b)$ crystal orientation. To find the thermodynamic ground state we studied the system at the lowest possible temperatures. We measured the dc and ac magnetization in magnetic fields up to 60 mT and at temperatures down to 800 μK with an rf SQUID magnetometer and the specific heat capacity of the material using the sample itself as a thermometer.

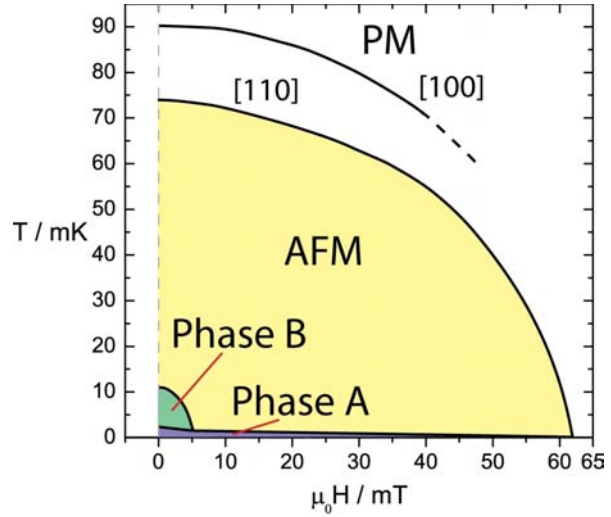


Figure 1: Phase diagram of YbRh_2Si_2 as we found last year. Below 10 mK two new phases labelled A and B showed up, obviously the ground states of the magnetic system. The lowest temperatures were around 800 μK .

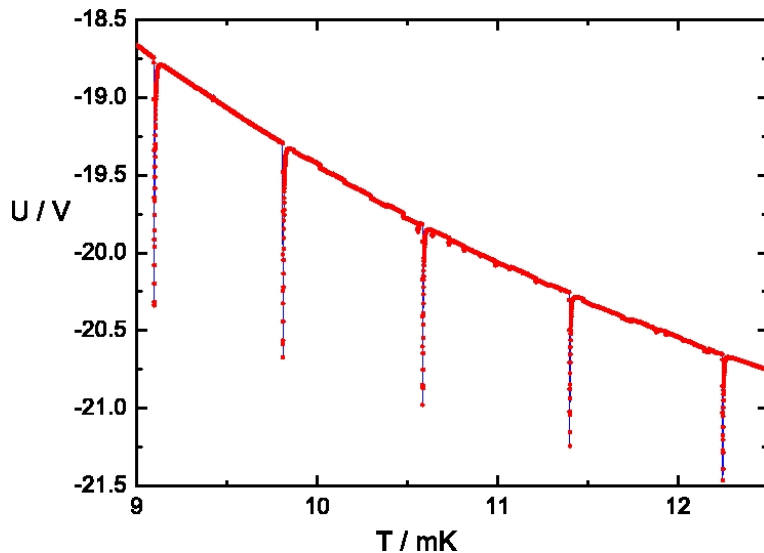


Figure 2: Series of heat pulses used to measure the specific heat capacity of YbRh_2Si_2 in different magnetic fields.

as a thermometer and we used the semi-adiabatic heat pulse method. The response of the dc magnetization is very fast and thus thermometry worked very well as shown in Fig. 2.

The experiments were done in our nuclear demagnetization cryostat with a final temperature of 400 μK . Temperatures were measured by pulsed NMR on Cu rods thermally anchored at the nuclear stage. The samples were clamped in a 5N silver rod which was screwed to the nuclear stage. The sample itself stuck contact-free in the pick-up coil of a superconducting flux transformer which transferred the signal into a niobium RF SQUID. Since there are no fast thermometers in the temperature range of interest, the only possibility was to use the sample itself as

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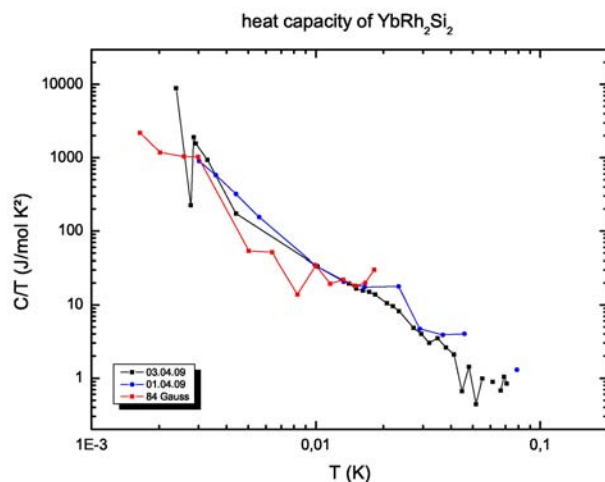


Figure 3: Result of specific heat capacity measurements on YbRh_2Si_2 in an applied magnetic field of 8.4 mT.

cating that it is probably of first order. Similar upturns showed up around the QCP. Final analysis of the data is under way, paying special attention to the question whether there are power laws in the temperature dependence of the specific heat capacity which could be attributed to different regimes in the phase diagram, e.g. Landau Fermi liquid, Kondo lattice, or magnetic ordering.

Finally, ac susceptibility measurements were done, again using the SQUID system as a sensitive detector. Through an additional coil inside the magnetometer the dc magnetic field was modulated with a small low frequency ac component and its response was detected by an analog Lock-In amplifier. Data were taken in different fields and with different frequencies. Best results were obtained using a 17.3 Hz modulation. Around both dc peaks at 70 mK and at 2.2 mK, strong positive magnetization signals were found, see Fig. 4. This indicates the existence of strong ferromagnetic correlations or domains in addition to the antiferromagnetic region below 70 mK.

In summary, we have continued experiments to characterize the two newly found phases in the Heavy Fermion compound YbRh_2Si_2 . It seems clear that the phases are not superconducting, at least not in a sizeable volume. The A phase is apparently the ground state of the Kondo lattice system which starts around 10 K. Obviously, there are antiferromagnetic as well as ferromagnetic tendencies at mK temperatures but the nature of the A phase ground state could not

As we discovered two new phases of YbRh_2Si_2 last year, see Fig. 1, our main focus this year was on the characterization of the new phases by specific heat capacity and ac susceptibility measurements. A remarkable feature of the phase diagram is that the phase A could extend all the way up to the QCP at 60 mT. A kink in this phase boundary around 6 mT was the first hint to the existence of phase B which has weaker magnetic signatures.

The specific heat measurements (see Fig. 3) showed a strong increase of C/T towards the A-phase transition, see Fig. 3, indi-

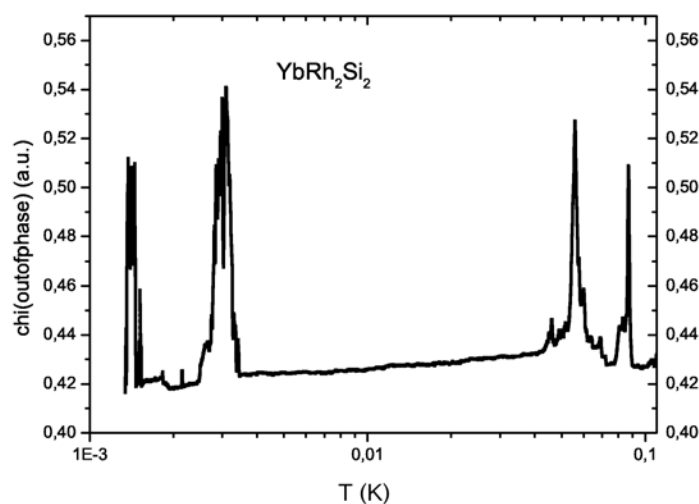


Figure 4: The ac susceptibility data show large signals from paramagnetic or ferromagnetic contributions just above and below $T_{\text{Neel}} \simeq 70$ mK and the A-phase transition, respectively.

be resolved yet. Further experiments are under way. Another fascinating question refers to the properties of the QCP. There could well be a connection between the suppression of the A state at the QCP, see Fig. 1, and the QCP itself. The latter could be driven not by antiferromagnetic fluctuations, as is assumed up to now, but by quantum fluctuations of the A-state because this is the lowest temperature phase bounding it.

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Search for the Fulde-Ferrell-Larkin-Ovchinnikov state in organic superconductors

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Quasi-two-dimensional organic superconductors belong to the most anisotropic compounds ever known. For magnetic fields applied perpendicular to the conducting layers the upper critical field is determined by the orbital effect (pair breaking due to the screening currents within the highly conducting layers) and the critical fields are quite small. But for magnetic fields applied parallel to the layers the orbital pair breaking is not effective and the critical fields can become very large. As already pointed out by Chandrasekhar [1] and Clogston [2] in 1962 there is another limit given by the Zeeman effect: when the Zeeman energy of the Cooper pair exceeds the condensation energy, superconductivity is destroyed. In the case of a BCS superconductor this limit is given by: $B_p/T_c = 1.84 \text{ T/K}$. In most superconductors the orbital pair breaking is dominant and the Chandrasekhar-Clogston limit (CCL) is not reached.

There are mainly two reasons why the CCL could be even exceeded. One of them is due to strong spin-orbit coupling and will not be discussed further here. The other is the so called FFLO state which was predicted in 1964 by Fulde and Ferrell [3] and independently by Larkin and Ovchinnikov [4]. This state is characterized by a spatial variation of the order parameter to lower the Zeeman energy and should show up only at temperatures below $T_0 = 0.56T_c$ and for very clean samples. At low temperatures an increase of magnetic field to the CCL is predicted to lead to a first order transition into the FFLO state. The latter is suppressed at fields considerably higher than the CCL. In the past the observation of this high field state was often announced, but in most cases it could not be confirmed.

As mentioned above the orbital effect is not effective in organic superconductors for magnetic fields applied within the layers and the critical fields become limited by the CCL. For instance we have studied in detail the anisotropy of the critical fields in α -(BEDT-TTF)₂KHg(SCN)₄ under an applied pressure of 2.8 kbar (critical temperature $T_c = 110 \text{ mK}$) by resistance measurements. We found an extraordinarily high anisotropy ratio of 300 between critical fields parallel and perpendicular to the layers. At low temperatures the critical field parallel to the layers went to saturation clearly showing limitation due to CCL. In 2007, a group in Geneva reported measurements of the critical fields parallel to the layers in κ -(BEDT-TTF)₂Cu(NCS)₂ by specific heat measurements [5]. They found at low temperatures a twofold transition hinting to a possible FFLO state. This seems to be up to now the most convincing evidence for the observation of the FFLO state.

However, the possibility to study the critical fields in κ -(BEDT-TTF)₂Cu(NCS)₂ is restricted to high field laboratories due to the CCL exceeding 20 T. We therefore decided to search for the FFLO state in another organic superconductor with lower critical temperature and critical fields: κ -(BEDT-TTF)₂I₃. This compound is very similar to κ -(BEDT-TTF)₂Cu(NCS)₂ in its electronic anisotropy and sample quality. However its critical temperature is 3.4 K and, therefore, the CCL is a factor of 3 lower than in the latter salt. It is known from literature [6] that the upper critical field parallel to the layers ($B_{c2\parallel}$) reaches 6.5 T at 0.5 K, but the temperature dependence of $B_{c2\parallel}$ is not known yet and the temperature dependence of $B_{c2\perp}$ is known only near T_c .

¹This work was done in collaboration with S. Pesotskii (Institute for Problems of Chemical Physics, Chernogolovka, Russia) with a support from DFG-RFBR, Grant No. 436 RUS 113/926.

To study the effect of magnetic field on the superconducting state in κ -(BEDT-TTF)₂I₃, we have performed magnetic torque measurements. The capacitive cantilever torquemeter was mounted on a rotating sample holder with an angular resolution of about 0.01°. We used a ³He cryostat at temperatures down to 0.42 K for the experiment. The single crystal [7] had a mass of 143 µg and was fixed on the torquemeter by a small amount of Apiezon grease. For determining the position of the sample with respect to the magnetic field, the angle θ was measured from the in-plane direction.

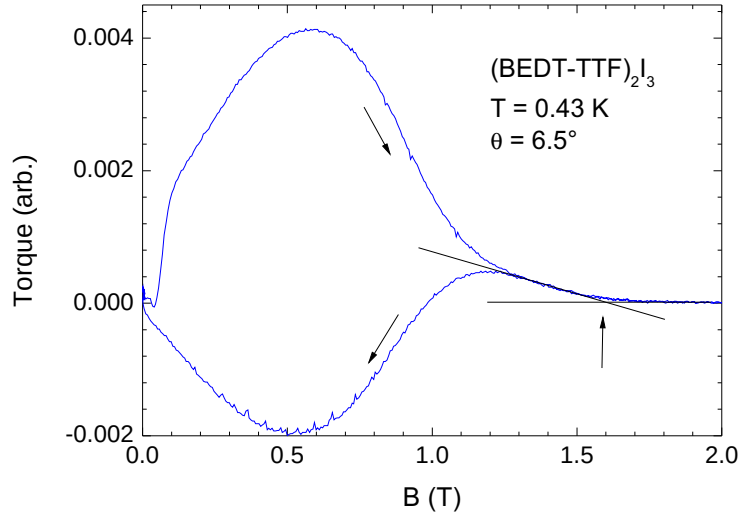


Figure 1: Typical torque signal at $T=0.43$ K for up and down sweeps of the magnetic field. The vertical arrow points to the upper critical field, defined as the intersection of the linear extrapolations from the normal state and from the reversible superconducting regime.

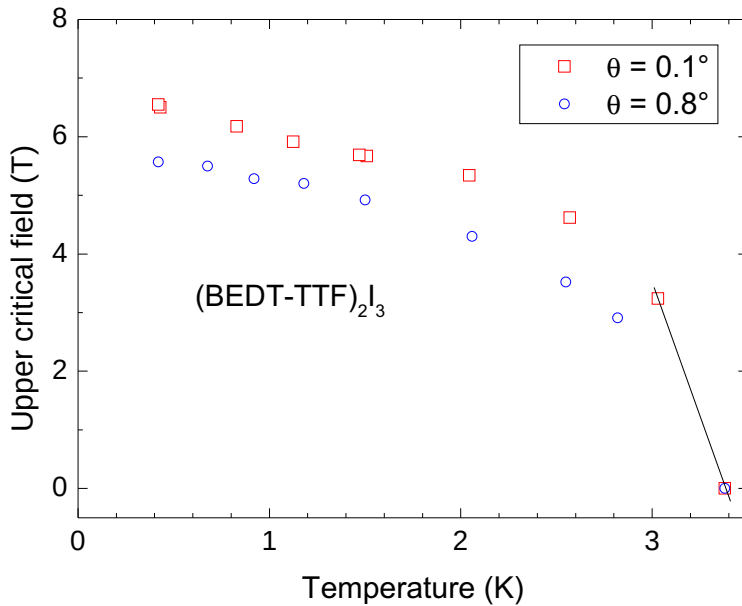


Figure 2: The upper critical field for two field directions almost parallel to the highly conducting plane.

the curve for $\theta=0.1^\circ$ is to a very good approximation identical to $B_{c2\parallel}$. The torque signal could be observed very near to T_c , the value of the transition temperature was determined by ac susceptibility measurements. The $B_{c2\parallel}(T)$ curve resembles that known from other organic metals. Near T_c the slope $B_{c2\parallel}/dT$ is very high, our data give a lower limit of 9 T/K. This high value is a strong evidence that the CCL will be effective at low temperatures. On decreasing the temperature the curve flattens, but never comes to saturation. The data even suggest an inflection point at about 1.5 K and $B_{c2\parallel}=5.8$ T, a value near to the CCL. The upper critical field values measured at $\theta=0.8^\circ$ do not show the inflection point and seem to saturate at about 5.7 T. The observed inflection point could be a hint to a possible FFLO state since it is expected below the

Fig. 1 shows a typical torque signal at $T=0.43$ K and $\theta=6.5^\circ$ and the way of definition of the upper critical field. The torque curve is - as expected for a type II superconductor - highly irreversible, but near B_{c2} there is a reversible part, which is extended near T_c and only short at low temperatures. The parallel direction can be determined very precisely: the torque signal varies very rapidly and changes sign at this direction. In Fig. 2 we have plotted the results for the upper critical field at $\theta=0.1^\circ$ and $\theta=0.8^\circ$. The

onset of the FFLO state at $T/T_c \leq 0.56$.

At low temperatures the presence of the FFLO state should lead to two subsequent transitions in the magnetic field dependence. We therefore studied very carefully the field dependence of the torque signal near the parallel direction at the lowest temperature. In Fig. 3 we show torque curves measured at three different angles near the parallel direction for the up and down sweeps of the magnetic field. There is almost no reversible part of the torque signal and no clear sign for a second transition within the superconducting state. (The small feature observed in the upsweep curves around 5.7 T could not be reproduced in a subsequent run with the same sample.) There is also a pronounced asymmetry: structures in the field dependence for positive angles could not be reproduced for negative ones.

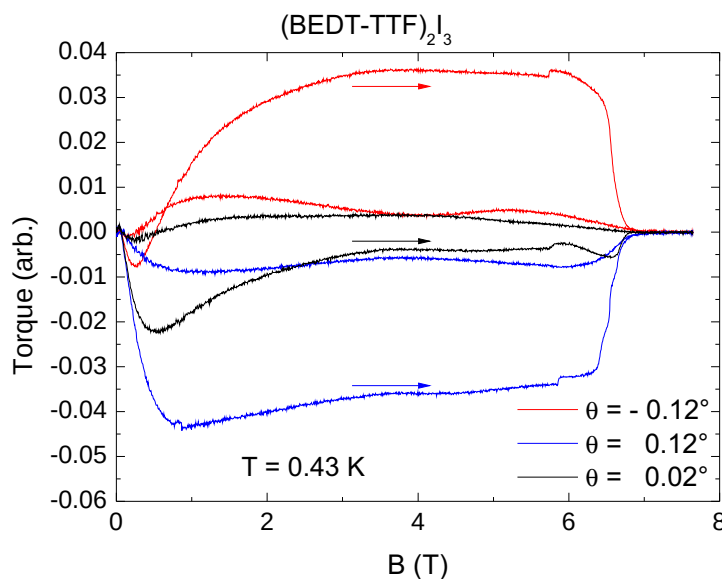


Figure 3: Magnetic torque for up and down sweeps of the magnetic field at polar angles very near to the parallel direction.

In conclusion, we have shown that the organic superconductor κ -(BEDT-TTF)₂I₃ is a possible candidate for the observation of a FFLO state. The very strong slope at T_c , the flattening of the curve near the CCL at about 6.5 T and the observation of an inflection point are in favor of the FFLO state. However, a direct evidence for a twofold transition could not be found in the torque measurements. Further studies are necessary to clarify this point.

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Fermi surface evolution in an electron-doped high- T_c superconductor revealed by magnetic quantum oscillations

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The Fermi surface topology and its evolution with doping is one of the most important issues related to the nature of charge carriers and various competing ordering phenomena in the high-temperature superconducting cuprates. The research has been pushed forward immensely by the recent discovery of slow magnetic quantum oscillations in the hole-underdoped superconductors $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ [1] and $\text{YBa}_2\text{Cu}_4\text{O}_8$ [2]. While the general trend is to associate these oscillations with small Fermi surface pockets, the latter apparently contradict the discontinuous Fermi arcs scenario derived from angle-resolved photoemission (ARPES) experiments and their origin is currently a matter of hot debate [3]. To solve the problem, it is pivotal to understand how the Fermi surface develops with changing the concentration and even the sign of charge carriers. However, direct probing of the Fermi surface by means of magnetic quantum oscillations has been restricted so far to hole-doped compounds with few selected doping levels, namely to the above mentioned underdoped yttrium-barium cuprates characterized by highly ordered oxygen and to cleanest samples of strongly overdoped $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ [4].

Here we report the observation of quantum oscillations in the interlayer magnetoresistance of the electron-doped superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (NCCO) at the optimal, $x=0.15$, as well as overdoped, $x=0.16$ and 0.17 , compositions [5]. The data obtained provide direct evidence for a well-defined continuous Fermi surface and clearly reveal its evolution with doping level. In particular, a dramatic change in the oscillation spectrum observed at increasing x from 0.16 to 0.17 is indicative of a topological transformation of the Fermi surface in the overdoped regime.

Compared to hole-doped cuprates, the electron-doped NCCO has a few advantages. First, the superconducting state of NCCO is restricted to the narrow doping interval $0.13 \leq n \leq 0.18$ (Fig. 1), where n is the number of doped electrons per Cu ion and $n=x$ due to the well-defined valences of the Nd^{3+} and Ce^{4+} ions. Hence, the whole relevant doping range can be controllably scanned by slightly varying x . Second, the upper critical field of NCCO is about an order of magnitude

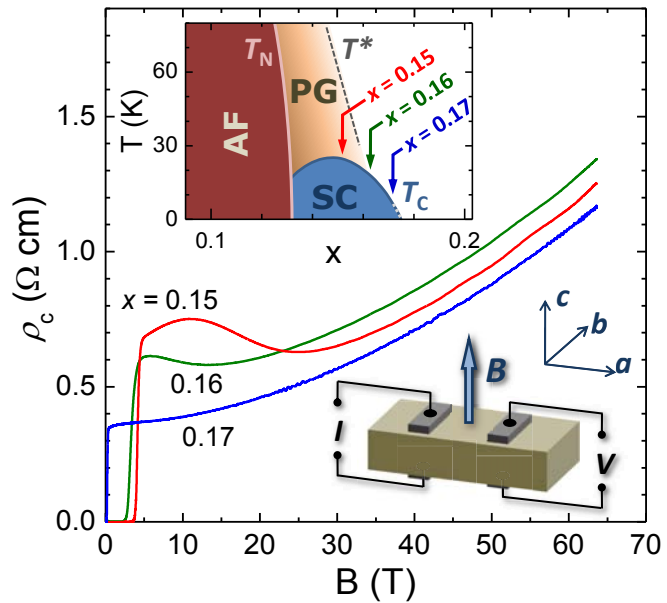


Figure 1: c -axis resistivity ρ_c of NCCO plotted versus magnetic field normal to the CuO_2 planes at $T=4$ K for different doping levels x . Upper inset: the currently accepted phase diagram of NCCO with the superconducting (SC), antiferromagnetic (AF), and pseudogap (PG) regions. Lower inset: the geometry of the experiment.

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lower than for hole-doped superconductors. Thus, for any doping level, we can access the normal state even at the lowest temperatures at magnetic fields $B \geq 10$ T (Fig. 1). This excludes potential ambiguities and complications in the interpretation of magnetic quantum oscillations associated with the vortex state of superconductors. Finally, the Fermi surface of NCCO is expected to be relatively simple: the material only contains a single conducting CuO_2 layer per unit cell, avoiding ambiguities with any bilayer potential.

Single crystals of NCCO were grown in an Ar/O_2 atmosphere using the traveling solvent floating zone method and annealed in pure argon at 950°C for 20 h in order to remove interstitial oxygen and strain in the crystal lattice. The high quality of the samples was ensured by structural analysis as well as by magnetic and resistive measurements. The experiments were done in a 70 T pulse magnet at the Hochfeld-Magnetlabor Dresden.

Figure 2(a) and Figure 2(b) show Shubnikov-de Haas (SdH) oscillations in the interlayer resistivity ρ_{osc} of NCCO crystals with three different doping levels, $x=0.15$, 0.16 and 0.17 , obtained from the raw data (Fig. 1) after subtracting the monotonic background. The data provides clear evidence for a well-defined closed Fermi surface, made up of fermionic charge carriers. For the optimally doped ($x=0.15$) and slightly overdoped ($x=0.16$) compositions shown in Fig. 2(a), the oscillation frequencies are $F_{0.15}=(290 \pm 10)$ T and $F_{0.16}=(280 \pm 10)$ T, respectively. The corresponding area of the extremal Fermi surface cross-sections is about 2.7 nm^{-2} , that is only $\simeq 1.1\%$ of the two-dimensional Brillouin zone, $S_{\text{BZ}}=253 \text{ nm}^{-2}$. A standard Lifshitz-Kosevich (LK) analysis of the oscillations observed on the optimally doped sample yields the cyclotron mass $m_c=0.6 \pm 0.05$ and Dingle temperature $T_D \approx 15$ K. The latter provides an estimate for the scattering time $\tau \simeq \hbar / 2\pi k_B T_D \approx 0.8 \times 10^{-13}$ s. This corresponds to a mean free path, averaged over the cyclotron orbit, of $\ell \sim \hbar (S/\pi)^{1/2} \tau / m_c \approx 14$ nm.

Whereas the oscillation frequencies are very similar for the $x=0.15$ and $x=0.16$ samples, a drastic change is observed on further increasing the doping level to $x=0.17$. The slow SdH oscillations vanish and, instead, much faster oscillations emerge at fields above 60 T [Fig. 2(b)]. Their frequency, $F_{0.17}=(10.7 \pm 0.4) \times 10^3$ T, corresponds to a large cyclotron orbit on the Fermi surface enclosing the area $S_{0.17}=(102 \pm 4) \text{ nm}^{-2}$ in $\mathbf{k}$ -space or, equivalently, $(0.405 \pm 0.015) S_{\text{BZ}}$.

The markedly different F obtained for the strongly overdoped ($x=0.17$) sample on the one hand and for the optimally doped ($x=0.15$) and slightly overdoped ($x=0.16$) samples on the other hand becomes apparent in Fig. 2(c). For $x=0.17$, the interpretation of our data looks straightforward: the size of the cyclotron orbit is fully consistent with the results of band-structure

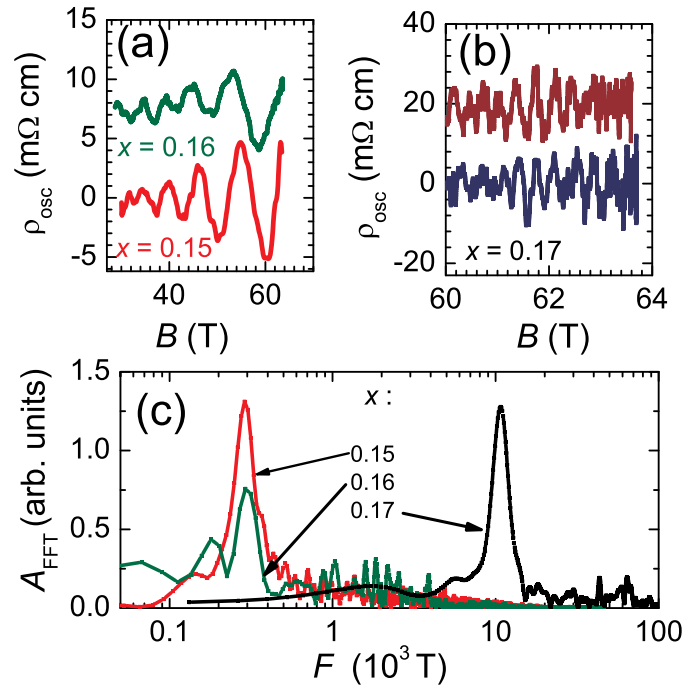


Figure 2: SdH oscillations in NCCO. (a) Slow oscillations in the optimally doped ($x=0.15$) and slightly overdoped ($x=0.16$) samples at $T=4.0$ K. (b) Fast oscillations in the sample with $x=0.17$ and $T=3.5$ K. Data from two different field pulses are shown. (c) Corresponding fast Fourier transform spectra of the oscillatory resistivity. For $x=0.17$, the spectrum corresponds to an average of the two data sets shown in (b).

calculations suggesting a single Fermi cylinder at the corner of the Brillouin zone, see Fig. 3(a). In contrast, the slow oscillations observed at the lower doping levels reveal a very small Fermi surface, indicating a qualitative change in its topology. This transformation can be explained by assuming that the commensurate antiferromagnetic (AF) superstructure, appearing in the electronic system of underdoped NCCO, survives up to the overdoped regime. The ordering potential leads to a reconstruction of the original Fermi cylinder, producing an electron and two small hole pockets in the reduced Brillouin zone, see Fig. 3(b). Using the standard two-band model [7] we fit the size of the hole pockets to that obtained from the oscillation frequency, obtaining an interband energy gap of $\Delta=64$ meV for $x=0.15$ and 36 meV for $x=0.16$.

It is tempting to assign the observed dramatic change in the SdH spectrum to a quantum phase transition associated with the Fermi surface reconstruction between $x=0.16$ and 0.17. However, at present we cannot unequivocally rule out the Fermi surface to be still reconstructed at $x=0.17$ due to a possible magnetic breakdown, allowing charge carriers to tunnel through a small gap which separates electron and hole pockets in k -space, see Ref. 8.

The combined data of our study and recent experiments [1, 2] suggests that in both hole- and electron-doped superconducting cuprates

the Fermi surface is reconstructed below a certain doping level. Whereas for the hole-doped cuprates no conclusive data on the evolution of the Fermi surface around optimal doping is available so far, our study of the electron-doped NCCO clearly shows that the reconstructed Fermi surface is present at optimum doping and even persists into the overdoped regime.

Our results apparently contradict ARPES and inelastic neutron scattering data on NCCO. In the ARPES experiments [6], no small hole-like Fermi pockets were observed. Moreover, a finite spectral weight at the intersections of the large Fermi surface with the reduced Brillouin zone boundary [dashed line in Fig. 3(b)] was reported for optimally and overdoped samples, suggesting no long-range ordering. The recent neutron scattering measurements [9] have revealed an AF correlation length $\xi_{AF} \leq 5$ nm in optimally doped NCCO. However, our observation of the slow SdH oscillations in samples with $x=0.15$ and 0.16 starting from implies the correlation length being at least of the order of the size of the coherent cyclotron orbit at $B \approx 30$ T which is estimated as ≈ 40 nm. A similar problem holds for the hole-underdoped $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ and $\text{YBa}_2\text{Cu}_4\text{O}_8$: the quantum oscillations point to a long-range ordering, which has not been revealed by any other experiment so far. While further studies are necessary for resolving this discrepancy, a plausible scenario is a field-induced AF ordering [10]. Indeed, indications of enhanced AF correlations in a magnetic field have been reported both for hole-doped [11] and for electron-doped [12] cuprate superconductors.

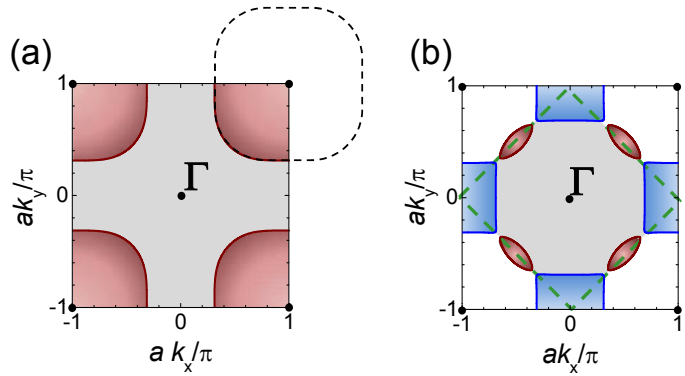


Figure 3: (a) Single-component Fermi surface corresponding to $x = 0.17$. The dashed line shows the large closed orbit responsible for the SdH oscillations. (b) Reconstructed Fermi surface comprising an electron and two hole pockets in the reduced AF Brillouin zone (dashed line). The hole pockets are responsible for the slow oscillations observed on the $x=0.15$ and 0.16 crystals.

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Magnetoresistance anisotropy and angle-dependent magnetoresistance oscillations in the electron-doped cuprate superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$

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Recent discoveries of magnetic quantum oscillations in hole- [1] and electron-doped [2] cuprate superconductors clearly demonstrate the importance of high-field magnetotransport experiments for exploring the Fermi surface in these materials. Besides quantum oscillations, semi-classical angle-dependent magnetoresistance oscillations (AMRO) are known to be a very efficient method for Fermi surface studies of layered systems, such as organic conductors [3]. AMRO have also been found in hole-overdoped $\text{Ti}_2\text{Ba}_2\text{CuO}_{6+\delta}$ [4], providing quantitative information on the Fermi surface geometry and temperature dependent anisotropic scattering. Aiming to find AMRO in the electron-doped superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (NCCO), we have performed detailed studies of the angular dependence of its interlayer magnetoresistance.

The experiments were done on single crystals with different Ce concentrations, covering the entire superconducting doping range, $x=0.13$ to 0.17 , see Ref. [2, 5] for sample preparation details. Steady magnetic fields $B \leq 28$ T were provided by the 20 MW resistive magnet at the Grenoble High Magnetic Field Laboratory. The samples were mounted onto a home-made two-axes rotating stage allowing an *in situ* rotation at a fixed B , at temperatures down to 1.4 K. The interlayer resistivity ρ_c was measured as a function of the polar angle θ between the field direction and crystallographic [001] axis of the sample, at different fixed azimuthal angles φ , as shown in Fig. 1(a).

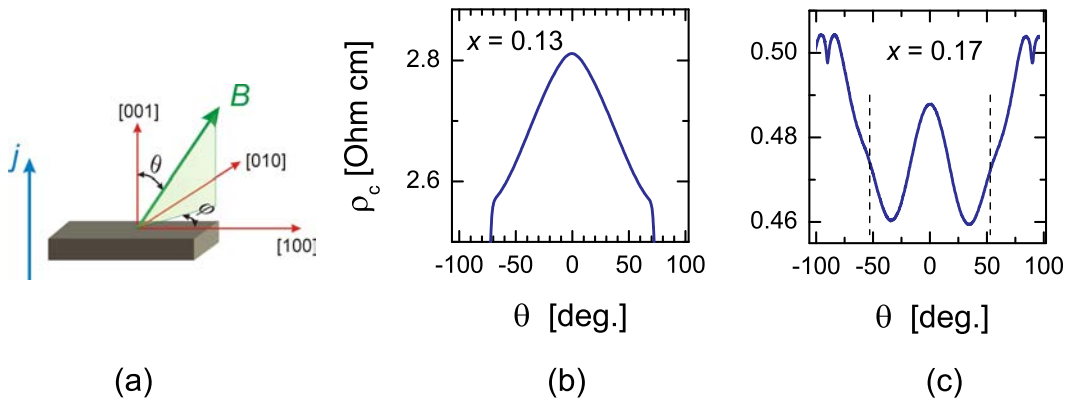


Figure 1: (a) Schematic illustration of the experimental geometry. (b) Interlayer resistivity ρ_c of an underdoped NCCO sample as a function of tilt angle θ . The range $-70^\circ < \theta < 70^\circ$ corresponds to the normal metallic state; the rapid drop of ρ_c outside this range is due to onset of superconductivity. (c) Angular dependence of the resistivity for a strongly overdoped NCCO crystal. Vertical dashed lines are drawn through the AMRO features, see text.

Depending on Ce concentration, two types of the angular dependence of ρ_c have been found. Figure 1(b) represents a typical behavior of underdoped samples. The resistivity is maximum at $\theta=0^\circ$ and gradually decreases on tilting the field towards conducting layers, until superconductivity sets in at high tilt angles [$|\theta| > 70^\circ$ for $x=0.13$, $T=1.4$ K, $B=28$ T, as shown in Fig. 1(b)].

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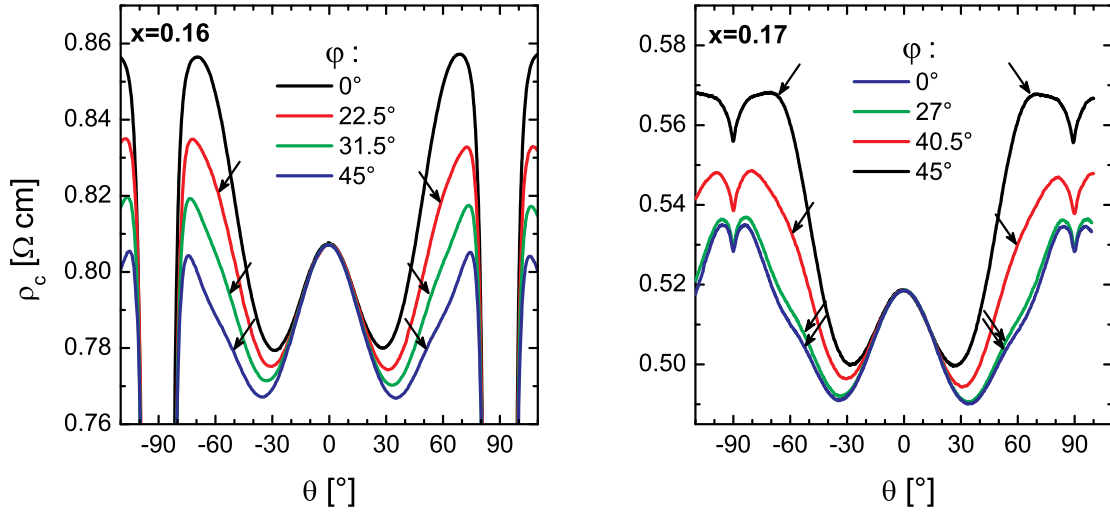


Figure 2: AMRO features (shown by arrows) obtained at different azimuthal angles φ for two different overdoped compositions.

The dome-like shape of the $\rho_c(\theta)$ curve is opposite to what one expects from a usual anisotropic metal. In the latter case, the magnetoresistance generally increases at increasing θ [3]. An explanation of the present anomalous behavior is most likely associated with the influence of the applied magnetic field on the ordered spin system. Indeed, recent data on the *in-plane* field rotation [6] point to a significant role of spin ordering on the magnetoresistance of underdoped NCCO. In our experiment, the field-induced readjustment of ordered spins is, at least, manifested in a small hysteresis in $\rho_c(\theta)$ curves observed at rotations around the $[1\bar{1}0]$ -axis (i.e., at $\varphi=45^\circ$). However, further detailed studies are necessary for clarifying the mechanism of coupling the interlayer magnetoresistance to electron spins.

For increasing Ce concentration to the optimal and, further, to the overdoped regime, the anomalous contribution to magnetoresistance weakens, giving way to the conventional mechanism associated with the orbital effect of the magnetic field on charge carriers. This gives rise to the positive slope of the angular dependence, $d\rho_c/d|\theta| > 0$ in an extended angular range, $30^\circ < |\theta| \lesssim 80^\circ$. This is shown in Fig. 1(c) for a strongly overdoped sample $x=0.17$. The most interesting feature in this range is a shallow hump superimposed on the monotonic slope around $\pm 52^\circ$. Though rather weak, this feature has been reproduced in all our experiments on several samples. Moreover, the same feature has been found on crystals with a lower doping level, down to $x=0.16$, see Fig. 2.

The position of the hump stays constant at changing temperature or magnetic field strength. It is, therefore, natural to associate it with a geometric effect of cyclotron orbits on the Fermi surface. For layered metals with cylindrical Fermi surfaces such effect is known as AMRO. The positions of AMRO are solely determined by the Fermi surface geometry and, therefore, independent of temperature and magnetic field. In the simplest case of a weakly warped Fermi cylinder with a circular cross section, the AMRO positions are determined by the condition: $|\tan \theta_i| = \pi(i - 1/4)/k_F d$, where k_F is the in-plane wave number, d is the interlayer period, and i is a positive integer. For a more realistic electron dispersion, the condition for AMRO is more complex and, in general, cannot be expressed analytically. Nevertheless, one can use the experimental data obtained for different azimuthal angles φ (Fig. 2) to determine the Fermi surface by a numerical fit based on the semiclassical kinetic equation.

While the numerical analysis of the observed AMRO is still in progress, an important quali-

tative information can already be obtained from the data in Fig. 2. For $x=0.16$ and 0.17 , the position of the AMRO features turns out to be the same for all φ values. Hence, the relevant Fermi surfaces should be identical for both compositions. This conclusion seems to contradict the Shubnikov-de Haas data [2] which exhibit a dramatic change in the oscillation spectrum at moving from $x=0.16$ to 0.17 . The apparent discrepancy can be resolved, if one takes into account a possible magnetic breakdown between the hole- and electron-like parts of the reconstructed Fermi surface. One can suggest, for instance, that the AMRO are caused by the same small hole-like part of the reconstructed Fermi surface which is responsible for the slow Shubnikov-de Haas oscillations observed on the $x=0.16$ samples. This would imply the Fermi surface to be still reconstructed even at the highest available doping $x=0.17$. The fast quantum oscillations found for this doping level at $B>60$ T [2] would then be due to magnetic breakdown which is enhanced in comparison with $x=0.16$. If this is the case, it would mean the magnetic ordering survives over the entire superconducting doping range, suggesting an intimate relation between magnetism and superconductivity in this material. At present, however, we cannot rule out that the AMRO are caused by the large orbit on the original, unreconstructed Fermi surface for $x=0.17$ and by a breakdown orbit comprising the small electron and hole Fermi pockets for $x=0.16$. To clarify the situation, an AMRO experiment at fields higher than 28 T, as well as further precise measurements of magnetic quantum oscillations in the over-doped regime would be very desirable.

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Electronic properties and phase transitions in the new layered organic conductor κ -(BETS)₂Mn[N(CN)₂]₃

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Organic charge transfer salts of bis(ethylenedithio)tetrathiafulvalene (BEDT-TTF) and its derivatives, being characterized by strong electron-electron and electron-phonon interactions, rather simple Fermi surfaces, and high crystal quality are excellent objects for studying correlation-induced instabilities of the normal metallic state. In particular, κ -(BEDT-TTF)₂X salts with polymeric anions have been of high interest, representing textbook examples of tunable Mott-insulating and charge-ordering systems. Another trend developing rapidly in the last years is synthesis and investigation of hybrid multifunctional molecular compounds combining conducting and magnetic properties. In such materials, conductivity is associated with π electrons in organic layers, whereas magnetism usually originates from localized spins of transition metal ions in insulating counterion layers. We have recently reported on a new organic conductor κ -(BETS)₂Mn[N(CN)₂]₃ (where BETS stands for bis(ethylenedithio)tetraselenafulvalene, a Se-substituted analog of BEDT-TTF) [1], which is a good candidate for studying the interaction between the strongly correlated conducting system and the magnetism of localized 3d electrons of Mn²⁺. This salt undergoes at low temperatures a metal-insulator transition which is also reflected in its magnetic properties. In the present work, we have studied the resistive behavior of κ -(BETS)₂Mn[N(CN)₂]₃ at different pressures and magnetic fields, aiming to determine its phase diagram and gain a deeper insight into its low-temperature electronic state.

The interlayer resistance of single crystals was measured by a standard 4-probe AC method. Care was taken to eliminate overheating by applied current, which was chosen in the range $10^{-8} - 10^{-5}$ A, depending on the resistive state of the sample. A ⁴He gas pressure setup was used for creating homogeneous quasi-hydrostatic pressure and its precise control at low temperatures. Magnetic fields up to 15 T were generated by a 15 T superconducting solenoid.

Figure 1(a) gives an overview on the temperature dependent interlayer resistance $R_c(T)$ of κ -(BETS)₂Mn[N(CN)₂]₃ at ambient pressure. Starting from room temperature, the resistance growth moderately, reaching a maximum of ~ 2 times its initial value at about 100 K. This behavior is typical of many layered organic metals, being caused, most likely, by a breakdown of the interlayer transport coherence and strong electron-phonon interactions [2]. At $T=103$ K the $R_c(T)$ de-

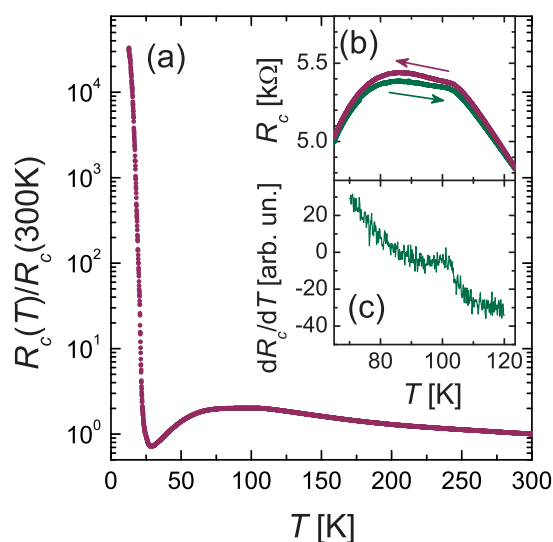


Figure 1: (a) Interlayer resistance of κ -(BETS)₂Mn[N(CN)₂]₃ as a function of temperature. (b) The same dependence in an expanded scale, around the superstructural transition; arrows indicate directions of temperature sweeps. One can see a hysteresis below the resistance anomaly at $T=103$ K. (c) Temperature derivative of R_c showing a discontinuous change at 103 K.

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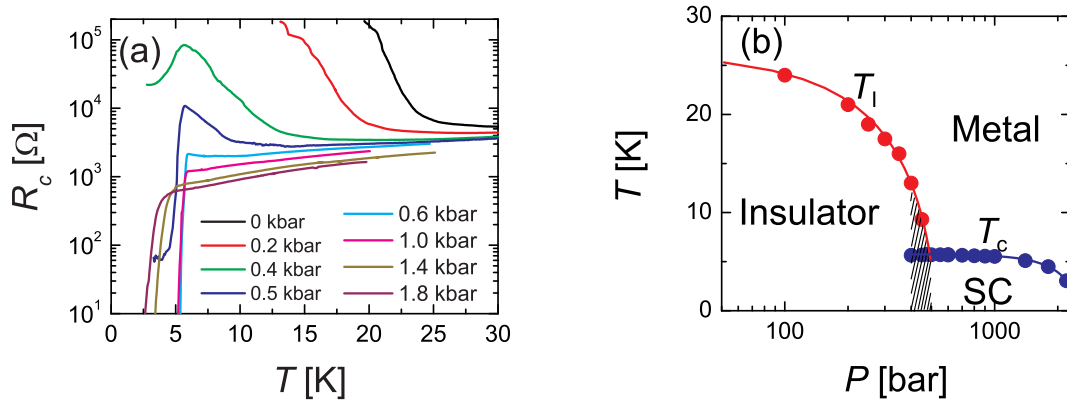


Figure 2: (a) Low-temperature behavior of the interlayer resistance at different pressures. The metal-insulator transition is rapidly suppressed at increasing pressure, giving way to superconductivity. (b) Pressure-temperature phase diagram based on the resistive measurements.

pendence exhibits a sharp bending accompanied by a hysteresis, as shown in Fig. 1(b) and Fig. 1(c). X-ray analysis [3] reveals an incommensurate superstructure with the wave vector $\mathbf{q}=[0, 0.42, 0]$ emerging at this temperature. At further cooling, the resistance displays a metallic behavior down to ~ 25 K and a metal-insulator transition at $T_I \approx 21$ K [1]. No changes of the crystal structure have been detected around this temperature [3]. This suggests that the transition is caused by electronic interactions.

The metal-insulator transition is very sensitive to pressure, as illustrated by Fig. 2. The transition temperature rapidly decreases with increasing pressure and, starting from 0.4 kbar, first signs of superconductivity are detected. However, it is not before 0.6 kbar that the insulating phase completely vanishes, and a homogeneous superconducting state sets in. The incomplete superconducting transition and a hysteresis between heating and cooling traces right above the transition indicate that the insulating and metallic phases coexist in the pressure interval between 0.4 and 0.6 kbar.

Figure. 2(b) shows also the pressure dependence of the superconducting transition temperature. In most organic superconductors, T_c rapidly decreases under pressure [4]. For example, the suppression rate $d \ln(T_c)/dP \approx 0.3 \text{ kbar}^{-1}$ is observed on $\kappa\text{-(BEDT-TTF)}_2\text{Cu(NCS)}_2$. By contrast, in the present compound $T_c(P)$ is almost constant in the interval between 0.5 and 1 kbar. Note, however, that at higher pressures T_c begins to decrease rapidly. One can suggest that flattening of $T_c(P)$ at $P < 1$ kbar is due to proximity of the insulating transition. Without the insulating instability T_c would increase at lowering pressure; however, coming closer to the metal-insulator phase boundary, the superconducting state becomes less stable and T_c does not show the expected increase.

The high pressure superconducting state is rapidly suppressed by applying a magnetic field perpendicular to conducting layers. At $P=1$ kbar, $T=1.4$ K, the normal state resistance is restored at ≈ 1.5 T, as shown in Fig. 3(a). With further increasing the field up to 4 T, the resistance is found to decrease. The reason for this negative magnetoresistance is still to be clarified. Above 4 T a conventional positive magnetoresistance sets in. For magnetic fields above 8 T, weak ($\Delta R/R \leq 5 \times 10^{-4}$) Shubnikov-de Haas (SdH) oscillations have been detected after subtracting the monotonic background, see inset in Fig. 3(a). The oscillation frequency, $F \approx 90$ T, corresponds to a very small Fermi pocket occupying about 1.5% of the first Brillouin zone area. Band structure calculations based on the room temperature crystal structure [3] do not predict such small pockets. We speculate that the pockets arise as a result of the reconstruction of the Fermi surface due to the 103 K superstructural transition. A similar transformation was

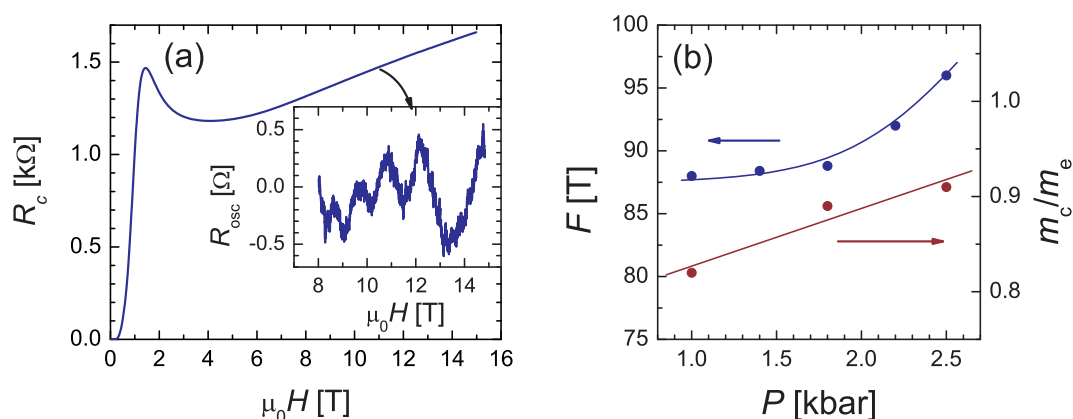


Figure 3: (a) Field dependence of the interlayer resistance. Inset: Shubnikov-de Haas oscillations after subtracting a monotonic background at $\mu_0 H > 8$ T. (b) Pressure dependence of the oscillation frequency (scale on the left) and cyclotron mass (scale on the right).

invoked to explain slow SdH oscillations in κ -(BEDT-TTF) $_2$ Cu[N(CN) $_2$]Br [5], which also undergoes a superstructural transition at about 200 K.

Figure 3(b) shows the pressure dependence of the SdH frequency $F(P)$ and that of the effective cyclotron mass m_c of the charge carriers responsible for the oscillations. The frequency grows by about 10% at increasing pressure from 1.0 to 2.5 kbar. This is a relatively large change but it is not unprecedented for the organic κ -type salts [5–7] and can likely be explained by an anisotropic compression of the crystal lattice. The cyclotron mass determined from the temperature dependence of the SdH amplitude is also found to increase by about the same amount in the interval between 1.0 and 2.5 kbar. This is, however, an unexpected result. Usually a pressure applied to an organic conductor increases the conduction bandwidth, thereby weakening many-body interactions and reducing the renormalized cyclotron mass [6]. The significant role of many-body interactions for the mass renormalization in the present compound is manifest in the rather large value, $m_c = 0.8 m_e - 0.9 m_e$ (m_e is the free electron mass), taking into account the very small size of the relevant Fermi surface. As seen from Fig. 2(b), at increasing pressure we move away from the metal-insulator transition, which should lead to a decrease of electronic correlations. Therefore, the positive slope of the $m_c(P)$ dependence looks surprising and needs to be clarified in future studies.

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Analytic methods for normal and pair-correlated Fermi systems

Dietrich Einzel

In this contribution, we reinvestigate the temperature dependence of certain thermodynamic (internal energy, entropy, specific heat capacity) and response functions of normal (compressibility, spin susceptibility) and pair-correlated (normal fluid density, spin susceptibility, magnetic penetration depth) Fermi systems. So far, these investigations have been limited to the use of approximate (for example Sommerfeld expansion) and numerical (for example the solution of the gap equation and the computation of local response functions in superconductors) methods. Here, we wish to present an *analytic* representation for these quantities, which enables us to describe on the one hand the *full* transition from the classical gas limit to the degenerate limit in normal Fermi systems, and, on the other hand, the temperature dependence of quasiparticle and condensate properties for *all* temperatures $T < T_c$ below the transition to the superconducting state. To start with, we assume that N Fermions of mass m and charge q in a volume V are characterized by a particle density $n = N/V$, a chemical potential $\mu(T) = k_B T \ln z$, with $z = \exp(\mu/k_B T)$ the so-called *fugacity*, a momentum $\mathbf{p} = \hbar \mathbf{k}$, and an energy dispersion $\epsilon_{\mathbf{k}} = \mathbf{p}^2/2m \equiv \xi_{\mathbf{k}} + \mu(T)$. The statistical properties of the Fermi system in its thermodynamic equilibrium state at a given arbitrary temperature T are then described by the Fermi–Dirac momentum distribution $n_{\mathbf{k}}^0 = 1/[\exp(\xi_{\mathbf{k}}/k_B T) + 1]$. In the superconducting state, it is well known that pairing correlations give rise to the spontaneous occurrence of an energy gap $\Delta_{\mathbf{k}}(T)$ below T_c , which leads to the following modification of the spectrum $E_{\mathbf{k}} = [\xi_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2]^{1/2}$ of thermal excitations, the so-called Bogoliubov quasiparticles or *bogolons*. The statistical properties of the bogolon gas can then be described by a modified Fermi–Dirac distribution $\nu_{\mathbf{k}}^0 = 1/[\exp(E_{\mathbf{k}}/k_B T) + 1]$. It turns out, that the *full* temperature dependence of *all* thermodynamic and response functions of the normal Fermi system can be expressed by only *two* so-called transition functions

$$t_n(z) = \frac{\text{Li}_{\frac{1}{2}}(-z)}{\text{Li}_{\frac{3}{2}}(-z)} ; \quad t_u(z) = \frac{\text{Li}_{\frac{5}{2}}(-z)}{\text{Li}_{\frac{3}{2}}(-z)} \quad (1)$$

which are functions of the fugacity z . These transition functions appear as ratios of certain so-called *polylogarithm* functions [1]:

$$-\text{Li}_s(-z) = \frac{z}{\Gamma(s)} \int_0^\infty \frac{dt t^{s-1}}{e^t + z} = \frac{z}{\Gamma(s+1)} \int_0^\infty \frac{dt t^s e^t}{(e^t + z)^2} = \sum_{k=1}^\infty \frac{(-1)^{k+1}}{k^s} z^k \quad (2)$$

with fractional index s . In (2), Γ denotes the Euler Γ -function. The thermodynamic properties of a normal Fermi system can then entirely be expressed through $t_n(z)$ and $t_u(z)$ and be discussed in terms of

- the internal energy $u(T)$

$$u(T) = \frac{U(T)}{V} = \frac{1}{V} \sum_{\mathbf{p}\sigma} \epsilon_{\mathbf{p}} n_{\mathbf{p}}^0 \equiv \frac{3}{2} n k_B T t_u(z) \quad (3)$$

- the equilibrium entropy $\sigma^0(T)$

$$\sigma^0(T) = -\frac{k_B}{V} \sum_{\mathbf{p}\sigma} \left[n_{\mathbf{p}}^0 \ln n_{\mathbf{p}}^0 + (1 - n_{\mathbf{p}}^0) \ln(1 - n_{\mathbf{p}}^0) \right] \equiv n k_B \left[\frac{5}{2} t_u(z) - \frac{\mu}{k_B T} \right] \quad (4)$$

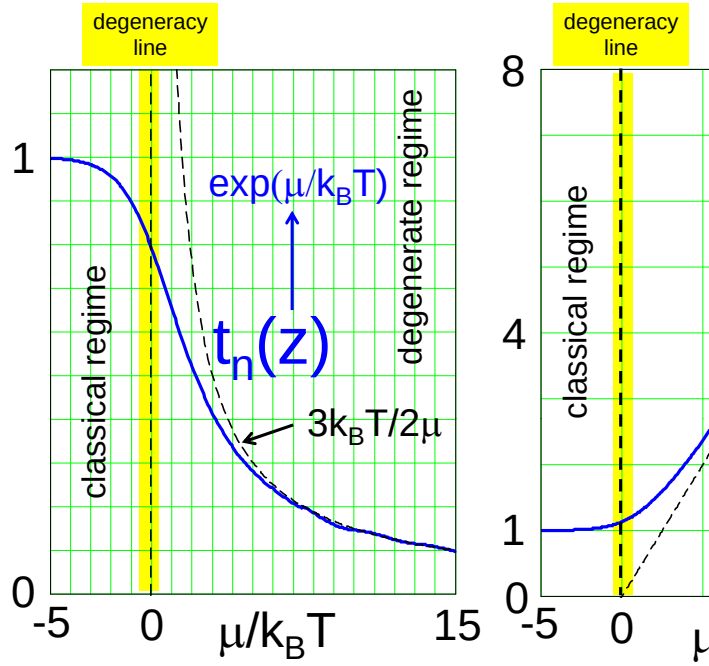


Figure 1: The transition functions $t_n(z)$ and $t_u(z)$ as a function of the reduced chemical potential $\mu(T)/k_B T$.

- the specific heat capacity $c_V(T)$

$$c_V(T) = \left(\frac{\partial u(T)}{\partial T} \right)_V = \frac{3}{2} n k_B \left[\frac{5}{2} t_u(z) - \frac{3}{2 t_n(z)} \right] \quad (5)$$

The relevant local response functions of the normal Fermi system are

- the compressibility $\chi_n(T)$

$$\chi_n(T) = \frac{\partial n}{\partial \mu} = \frac{n}{k_B T} t_n(z) \quad (6)$$

- the spin susceptibility $\chi_s(T)$

$$\chi_s(T) = \mu_B^2 \frac{\partial n}{\partial \mu} = \mu_B^2 \frac{n}{k_B T} t_n(z) \quad (7)$$

where $\mu_B = e\hbar/2mc$ denotes the Bohr magneton.

Clearly, in the classical limit $T \rightarrow \infty$ ($z \rightarrow 0$), both transition functions $t_n(z)$ and $t_u(z)$ tend to 1 and we recover the classical gas limit for the expressions (3)-(7). In the degenerate limit $T \rightarrow 0$ ($z \rightarrow \infty$), on the other hand, one observes that

$$\lim_{z \rightarrow \infty} t_n(z) = \frac{3k_B T}{2\mu(0)} - \frac{\pi^2}{8} \left(\frac{k_B T}{\mu(0)} \right)^3 - \dots ; \quad \lim_{z \rightarrow \infty} t_u(z) = \frac{2\mu(0)}{5k_B T} + \frac{\pi^2}{6} \frac{k_B T}{\mu(0)} - \dots$$

Note, that in the degenerate limit, one obtains, as expected, the result $\partial n / \partial \mu = 3n / 2\mu(0) \equiv N_F$, with N_F the density of states at the Fermi surface for both spin projections. In Fig. 1 we have plotted the transition functions $t_n(z)$ and $t_u(z)$ versus the reduced chemical potential $\mu/k_B T$. It is worth noting, that in the regime of high $\mu/k_B T$, the difference between the dashed and

full lines marks the deviations of $t_n(z)$ and $t_u(z)$ from their degenerate limit forms, and thus represents an *analytical* counterpart for the Sommerfeld expansions, which have traditionally been necessary to explain this deviation.

In the superconducting state, we wish to restrict our considerations to the case of isotropic energy gaps $\Delta_k = \Delta$, at least for the time being, and to a discussion of

- the normal fluid density

$$n^n(T) = nY(T) \quad (8)$$

- the magnetic penetration depth

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1 - Y(T)}} ; \quad \lambda^2(0) = \frac{mc^2}{4\pi nq^2} \quad (9)$$

- the spin susceptibility

$$\chi_s(T) = \mu_B^2 \frac{\partial n}{\partial \mu} Y(T) \quad (10)$$

All these quantities are thus seen to be characterized by the temperature–dependent so–called Yosida function $Y(T)$ [2]

$$Y(T) = \int_{-\mu}^{\infty} d\xi_{\mathbf{p}} \left(-\frac{\partial v_{\mathbf{p}}^0}{\partial E_{\mathbf{p}}} \right) = \frac{1}{4k_B T} \int_{-\mu}^{\infty} \frac{d\xi_{\mathbf{p}}}{\cosh^2 \frac{E_{\mathbf{p}}}{2k_B T}} = \int_0^{\infty} \frac{dt}{\cosh^2 \sqrt{t^2 + \left(\frac{\Delta}{2k_B T} \right)^2}} \quad (11)$$

Close to the transition, in the so–called Ginzburg–Landau (GL) regime, the Yosida function $Y(T)$ can be represented by set of k Ginzburg–Landau coefficients y_ν :

$$\lim_{T \rightarrow T_c} Y(T) \approx Y_{GL}(k, T) = 1 - \sum_{\nu=1}^k y_\nu \left(1 - \frac{T}{T_c} \right)^\nu \quad (12)$$

The first few y_ν are $y_1=2, y_2=1+2a_2/a_1^2, \dots$, with coefficients

$$a_\nu = 2(-1)^\nu \frac{(2\nu-1)!!}{(2\nu)!!} \frac{2^{2\nu+1}-1}{2^{2\nu+1}} \zeta(2\nu+1)$$

Here ζ denotes the Riemann ζ –function. In the opposite limit of low temperatures, $Y(T)$ can be expressed through ℓ terms of a low temperature expansion, which should account *both* for powers of $k_B T / \Delta$ and $\exp(-\Delta/k_B T)$:

$$\begin{aligned} \lim_{T \rightarrow 0} Y(T) \approx Y_{LT}(\ell, T) &= \sum_{\mu=1}^{\ell} (-1)^{\mu+1} Y_0(T, \mu\Delta) \\ Y_0(T; \mu\Delta) &= \sqrt{\frac{2\pi\mu\Delta}{k_B T}} e^{-\frac{\mu\Delta}{k_B T}} \left\{ 1 + 3\frac{k_B T}{8\mu\Delta} - \frac{15}{2} \left(\frac{k_B T}{8\mu\Delta} \right)^2 + \dots \right\} \end{aligned} \quad (13)$$

These two expansions can eventually be combined [2, 3] at a characteristic temperature T_0 , using the smooth crossover function

$$f(T) = \Theta(T, 0.65T_c, 0.002) ; \quad \Theta(T, T_0, q) = \frac{e^{(T-T_0)/qT_c}}{1 - e^{(T-T_0)/qT_c}} \quad (14)$$

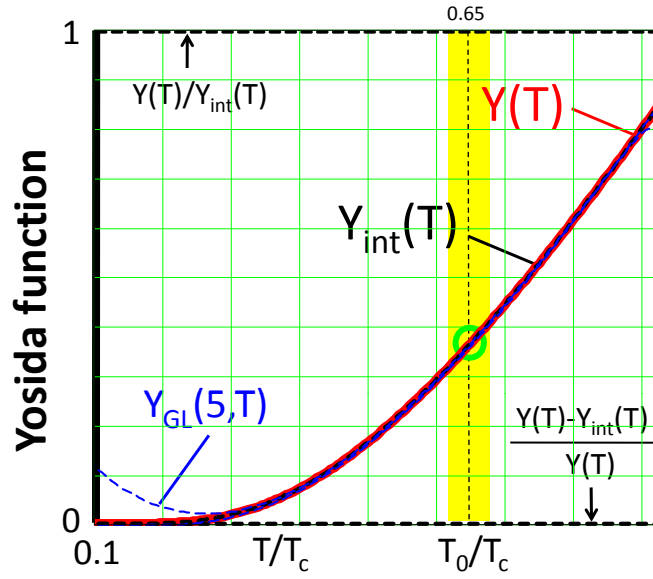


Figure 2: The interpolated Yosida function $Y_{\text{int}}(T)$ vs. reduced temperature T/T_c . Also shown is the exact numerical result $Y(T)$ and the approximations for $Y(T)$ in the Ginzburg-Landau- [$Y_{\text{GL}}(T)$] and in the low temperature [$Y_{\text{LT}}(T)$] regime.

Note that $\Theta(T, T_0, q)$ approaches the Heaviside step function $\Theta(T - T_0)$ in the limit $q \rightarrow 0$. The result of this combination will, in what follows, be referred to as $Y_{\text{int}}(T)$:

$$Y_{\text{int}}(T) = Y_{\text{GL}}(5, T)f(T) + Y_{\text{LT}}(3, T)[1 - f(T)] \quad (15)$$

and has been plotted as a function of reduced temperature in Fig. 2, together with an exact numerical evaluation of $Y(T)$ and the results for $Y_{\text{GL}}(T)$ and $Y_{\text{LT}}(T)$. It is quite remarkable, that the regions of validity of the Ginzburg-Landau and low temperature expansions extend to $\geq 0.3T_c$ (GL) and $\leq 0.9T_c$ (LT), respectively. It turns out, that the typical error of both $Y_{\text{GL}}(T)$ and $Y_{\text{LT}}(T)$ at the temperature T_0 , is of the order of 0.1%. Therefore, the function $Y_{\text{int}}(T)$ may be viewed as a quasi-analytical representation of the quasiparticle Yosida function $Y(T)$.

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How structure influences material properties and sensor performance

B. A. Hermann

Nanoscale research has opened up a new dimension for studying material properties. Using scanning tunneling microscopy (STM), the surface electronic properties and structure of materials can be investigated on the atomic or molecular scale. Applications towards the fields of surface coating, sensors, catalysis, layered superconductors as well as molecular electronic devices have already been demonstrated. In all these cases a local correlation in structure and/or electronic properties is responsible for the material function. STM allows the investigation of the surface electronic properties of (weakly) conducting bulk materials, adsorbed layers and sensors. This microscopy technique elucidates in very high resolution the surface atomic/molecular configuration, thus delivering important information on the possible connection between structure and complementary material properties.

The relevant questions to be addressed are:

a.) In bulk materials i.e. layered superconductors [1]: how are the electronic properties and structure of the topmost termination layers connected with local electronic material properties i.e. conductance and the superconducting energy gap? Is the termination layer possibly reconstructed and how would such a reconstruction influence the observed contrast in the STM images?

b.) In adsorbed layers [2]: How do adsorbed self-organized molecular monolayers order? How does this order affect material properties like chirality, hierarchy and pattern symmetry? In connection with simulation experiments: How can the geometric structure of the molecule influence the monolayer ordering and subsequently its materials properties? How is the dynamic behavior of molecular reorganization dictated by the free-energy landscape of the molecules [3]?

c.) In case of sensor surfaces in connection with cantilever array sensor measurements [4]: how does the local molecular composition and accessibility of key-lock binding pockets influence the sensor performance? Is the selectivity and sensitivity connected to a certain sensor surface topology? How can the sensor reproducibility be improved by surface investigation?

As mentioned, we use scanning probe techniques successfully in combination with simulation and cantilever array sensors techniques to address surface structure related questions in the field of low dimensional correlated systems.

In various in-house, Munich-wide and international collaborations, the group currently focuses on structural and electronic properties of molecular assemblies and superconductors in order to pursue material driven and (bio)chemical applications as well as to understand the compounds or composite structures of low-dimensional systems in principle, e.g. a proof of principle experiment based on carbohydrate-protein recognition is currently performed with cantilever arrays.

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Organic superconductors

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N.D. Kushch¹

Scanning tunneling microscopy (STM) is an excellent tool to study the electronic surface morphology as well as spectroscopic details revealing the local gap structure of organic superconductors. κ -(BEDT-TTF)₂Cu(NCS)₂ (κ -di[bis(ethylenedithio)tetrathiafulvalene] di(thiocyanate)cuprate) has one of the highest transition temperatures ($T_c = 10.4$ K) among organic superconductors. The bc plane of κ -(BEDT-TTF)₂Cu(NCS)₂ single crystals of different ages was investigated with STM and the images were compared with state-of-the-art CASTEP theoretical density functional theory (DFT) based simulations of a relaxed and not relaxed surface [1]. The simulated STM image of the relaxed surface accounts for all major features observed in the STM images, see Fig. 1.

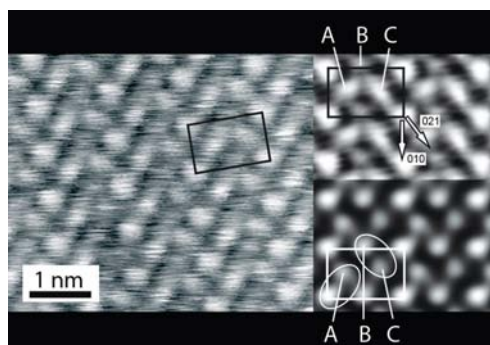


Figure 1: Drift corrected STM image of the bc plane of a few months old κ -(BEDT-TTF)₂Cu(NCS)₂ crystal ($U_{\text{Bias}} = +30$ mV, $I_t = 3$ pA, $5.0 \text{ nm} \times 4.3 \text{ nm}$, ambient conditions); the black rectangle marks a unit cell. The right part shows each four complete (2×2) unit cells: The top right image was gained from a correlation averaged cut of the STM-measurement; The bottom right graphics displays a convoluted DFT based simulation for comparison with the STM-measurements.

Via a surface relaxation in the Broyden-Fletcher-Goldfarb-Shanno (BFGS) quasi-Newton scheme, we can account for the recently reported symmetry-breaking in the STM measurements as well as the enhanced brightness along the $[010]$ -direction. A close match of the STM measurements is observed to the calculated local density of state (LDOS) of a such relaxed bc plane of κ -(BEDT-TTF)₂Cu(NCS)₂ crystals (cation layer). This suggests that the symmetry-breaking and the enhanced brightness are indeed caused by a surface relaxation, see Fig. 2.

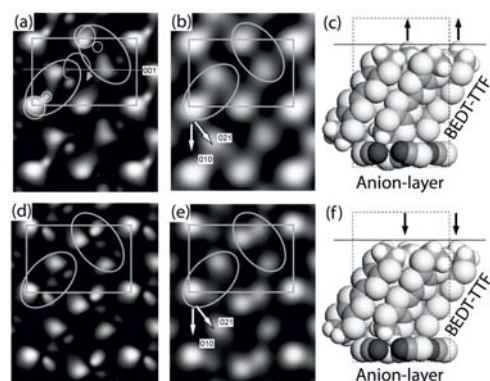


Figure 2: Cut through the isosurface of a DFT based simulation of the bc plane of a relaxed and not relaxed κ -(BEDT-TTF)₂Cu(NCS)₂ crystal surface, with each sub-image showing roughly 1×2 unit cells: (a) Revealing a relaxed surface and (b) a convoluted (Gauss function treated) simulation imitating a finite STM-tip on the relaxed crystal surface. (c) Side view of a space-filling depiction of the relaxed unit cell gained by a quasi-Newton-scheme optimization. In the relaxed unit cell the topmost hydrogen atoms stretch up (marked with arrows). (d) Illustrating a bare and (e) a convoluted simulation imitating a finite STM-tip on the not relaxed crystal surface. (f) Side view of the non-relaxed unit cell for comparison.

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Molecular self-organization

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The last decade has seen a steady increase in research devoted to the bottom-up construction of nanomaterials by the autonomous self-assembly of molecules on well-defined surfaces with the ultimate goal of creating functional nanosystems. Especially hierarchical molecular assemblies have drawn increasing interest in recent years because of the possibility of fabricating highly ordered functional superstructures from elementary building units. A hierarchical order of building blocks can lead to a wide variety of patterns possibly bearing various functions. Scanning tunneling microscopy (STM) of Fréchet-dendrons revealed an unprecedented variety of patterns with up to eight stable hierarchical ordering motifs. Can such a variety of patterns be predicted? Relying on molecular mechanics methods the essential molecular properties were condensed in a coarse-grained interaction-site model. We employed an independent Monte Carlo (MC) approach with this coarse grained interaction site model to reproduce the pattern diversity [1] found in the STM investigation as well as its local and global ordering, see Fig. 1. Furthermore, in a zero temperature analysis we could also successfully predict the ground state pattern in line with experimental findings upon heating [2]. A newly predicted local ordering motif has even been experimentally verified afterwards.

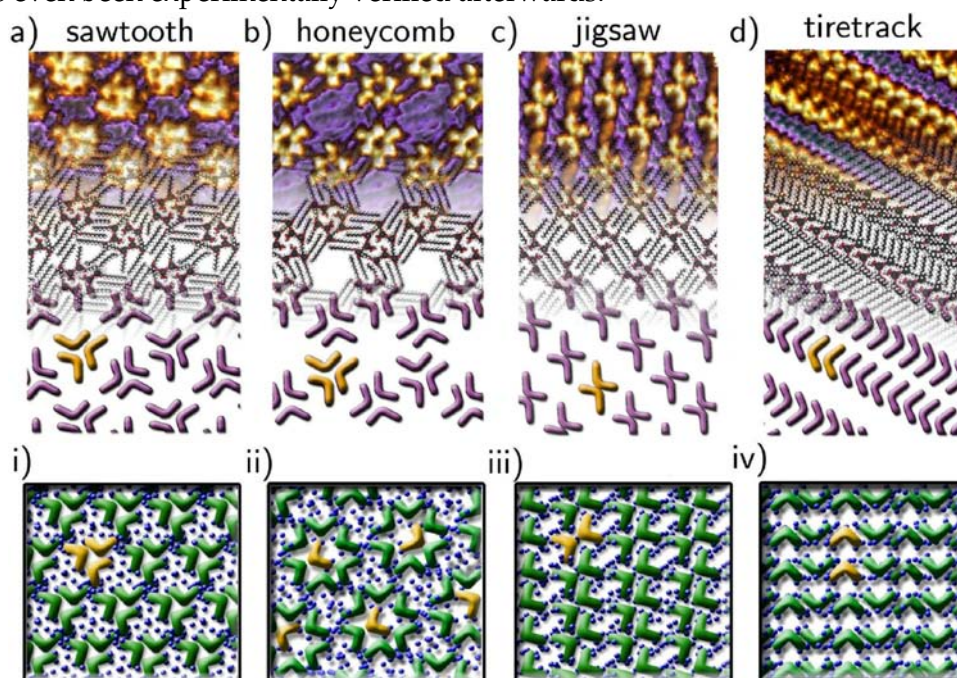


Figure 1: STM images of four experimentally found patterns, (a)–(d), of a Fréchet-dendron and independent predictions by Monte Carlo (MC) simulations, (i)–(iv). In each column from top to bottom, the high-resolution measurements are faded into the corresponding MM energy minimizations. They are further reduced to a core representation indicating the long-range ordering motif of the respective assemblies as well as the local ordering motif displayed in yellow. The MC simulations of this coarse-grained model predict four (i)–(iv) patterns with striking resemblance to the measurements in long range and local ordering. (a)–(d): $12.5\text{ nm} \times 22\text{ nm}$, $U_{\text{Bias}} = -(700\text{--}800)\text{ mV}$, $I_t = 5\text{--}30\text{ pA}$.

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This multitude of patterns allows the characterization of a rather complex free-energy landscape. We mapped the progression of the free-energy landscape from simple to more complex Fréchet-dendrons molecules. The depth of the local minima in the free-energy landscape, corresponding to the various metastable phases, were calculated employing molecular mechanics (MM) simulations, the starting values of which were found from the STM measurements. Additionally, the STM-images are simulated using density functional theory (DFT) calculations of the integrated local density of states (LDOS). Furthermore, the structure of the patterns was changed by utilizing heterogeneous assemblies. Hereby the guest molecule introduced to the system has been systematically varied, allowing a detail study of the guests influence on the local ordering.

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Towards the best possible cantilever array application: Understanding and sensor development

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A. Rubio³

Carbohydrate interactions play a major role in many biological processes, including cell-cell recognition and host-pathogen infection. The fight of dangerous diseases such as HIV, anthrax or malaria relies heavily on the understanding of carbohydrate-protein interactions and could thus benefit greatly from new sensing techniques. Owing to recent advances in synthesis carbohydrate-based research is now catching up fast to the more established fields of genomics and proteomics. This rising field of research depends on safe testing environments to promote drug design and vaccine development - the robust and scalable cantilever sensor platform could possibly match these requirements.

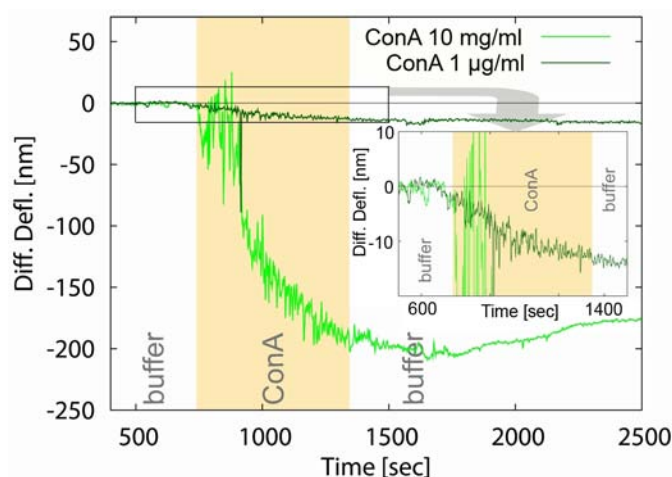


Figure 1: The dark green signal (see also inset) illustrates the sensitivity of the carbohydrate sensor after an injection of ConA of high concentration (10 mg/mL, light green): The sensor is able to detect nanomolar concentrations of ConA (1 µg/mL, dark green curve). The inset displays the differential deflection of nanomolar injection on an enlarged y-axis.

To demonstrate the suitability of cantilever arrays in carbohydrate research, the reproducibility, sensitivity and selectivity of these sensors has to be shown in a proof-of-principle experiment [1].

Cantilever array sensors are a new and innovative sensing technology. In contrast to many other surface bound techniques, the cantilever array technology operates label-free and offers scalability to very large arrays (e.g., to 1024 sensors [2]). Parallel processing allows on-line references to exclude unspecific binding. For establishing cantilever arrays as a reliable and practicable sensor method, it is necessary to understand the underlying mechanisms of signal development and progression. To elucidate these processes we closely study the details of sensor functionalization and analyte binding. As mentioned our current investigated system stems from the fast expanding area of glycomics, the field of carbohydrate research.

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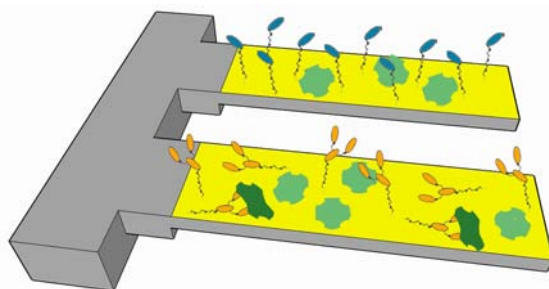


Figure 2: Schematic illustration of the origin of the differential cantilever signal. The specific binding of ConA to the mannose derivatives contributes significantly to the signal, while the somewhat larger number of ConA proteins adsorbing on unspecific binding sites of the trimannose cantilevers (due to the lower carbohydrate density) may give an additional contribution to the sensor signal.

In collaboration with Prof. P. Seeberger, MPI of Colloids and Interfaces and Prof. A. Rubio, University of San Sebastián we introduce for the first time the method of cantilever sensing to the study of carbohydrate-protein interactions. We functionalize our sensor surface with mannose derivatives to mimic a specific cell surface docking site. For a proof-of-principle detection experiment, we chose the lectin Concanavalin A (ConA) as a model protein. ConA binds specifically to mannose derivatives, but in much lower affinity to other carbohydrates such as galactose. Thus we functionalize half of our parallel sensing cantilevers with galactose molecules as a reference to extract the contribution of unspecific binding from the sensor signal.

To verify the performance of the specific mannose-ConA binding we show:

Reproducibility: ConA detection can be repeated several times using one array and can be reproduced on several other, independently functionalized, cantilever arrays.

Sensitivity: Diluting the protein down to the nanomolar range (see Fig. 1), ConA is successfully detected to bind to the mannose sensor surface in clinically relevant concentrations (factor 10-100 times better than quartz crystal microbalance (QCM) [3] and surface plasmon resonance (SPR) [4]).

Selectivity: The selectivity of the ConA-mannose recognition is demonstrated by competitive inhibition with free mannose in the running buffer.

Robustness: Due to the small and resilient carbohydrate molecules (functionalizing our sensor surface) the cantilever array may be reused many times as well as be stored at -20°C for later experiments.

Understanding the Signal Composition: We carefully studied the individual sensor responses of mannose and galactose functionalized cantilevers. Moreover with clever designed reference experiments we gained an understanding on the sensor's signal progression. The model displayed in Fig. 2 elucidates our current understanding of the dominant surface processes influencing the sensor performance.

Thus, in a proof of principle setup [1], we are able to reproducibly detect selective binding of the lectin Concanavalin A (ConA) to the mannose functionalized sensor against a non-specific galactose reference down to nanomolar sensitivity (displaying a factor 10 – 100 better resolution compared to conventional surface bound methods). Next, we aim at biochemically more relevant systems: *E. coli* bacteria, a widely established bacterial model system in biochemistry. Other cell-related projects together with Dr. D. Heinrich, Lehrstuhl Prof. Dr. J. Rädler are in planning.

For the implementation of these projects, we acquired new cell-handling equipment including an incubation shaker and vacuum concentrator. Together with the cantilever functionalization

unit and sensor platform these are now located inside a contaminant-free, laminar flow box (see facilities section). An autoclave system is installed. Experiments employing these new facilities are currently under way.

Hence, elucidating the structural influence of surface topographic and electronic effects on the material properties has deepened our understanding of complex molecular systems. Its application towards sensorics based on (bio)molecular recognition will be greatly aided by the new cell-handling facility.

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New laser beam optics for the laser MBE system

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Multifunctional oxides have been in the focus of basic and applied research at the WMI for many years. Single crystalline, epitaxial thin films of ferromagnetic, ferroelectric, and semiconducting oxides are grown in an ultra-high vacuum (UHV) laser-MBE system using pulsed laser deposition (PLD) with a KrF excimer laser at a wavelength of 248 nm. To further enhance the performance of the system and to further improve the sample quality, we replaced the optical path for the excimer laser beam by a completely new beam optics consisting of a laser telescope lens system and a new UHV laser entrance port. The goal was to extend the range of the available laser fluence at the PLD target as well as to reduce inner coating and increase the cleaning interval times of the laser entrance window. The new system also allows for a fast computer-controlled change of the laser power density. This is required for the deposition of complex heterostructures.

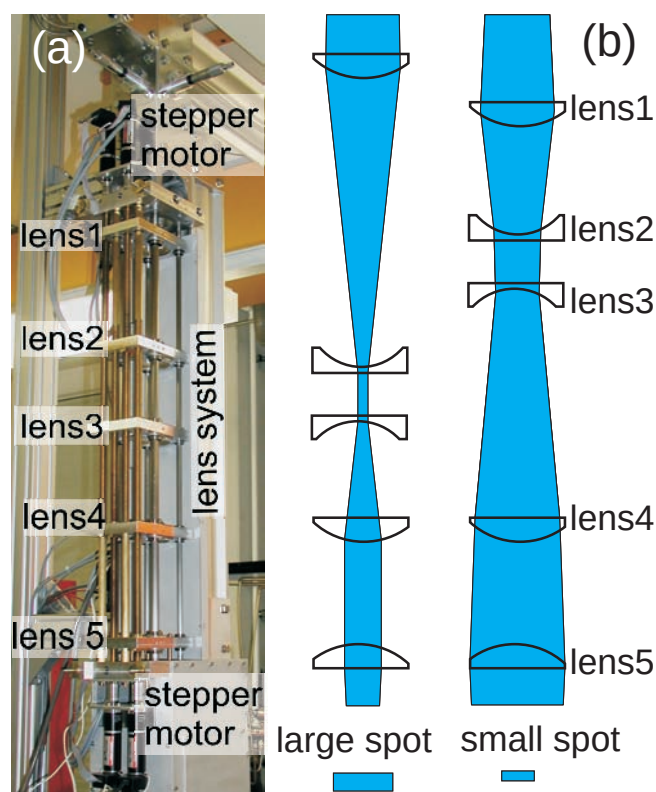


Figure 1: (a) Photograph of the installed laser beam optics, with lens system, stepper motors and lens carriers. (b) Schematics of the system. The spot size at the PLD target is changed by moving the lenses 1 to 3 and keeping the lenses 4 and 5 at a fixed position.

The main part of the new optical path is a telescope system consisting of 5 lenses in total (Fig. 1). Lenses 1 to 4 are mounted on 4 motor-driven lens carriers allowing a vertical movement across a total height of 120 cm. The lens carriers are attached to 4 stepper motors, each connected to a controller with a spatial resolution of less than 0.005 mm. They are controlled by a PC, thus allowing full automation of the lens system itself. The lenses are arranged such that they build up a classical telescope zoom optics, creating a sharp image of the excimer laser's rectangular aperture at the PLD target. Thereby, the positions of lenses 1 to 3 determine the size of the image, lenses 4 and 5 assure perfect focusing. The lens system allows to change the size of the rectangular excimer laser spot on the PLD target between 1.2 mm² and 12 mm² without losing sharpness of the spot itself. The corresponding on-target laser fluences are 0.5 J/cm² to 5.5 J/cm², which is 1.5 J/cm² higher as compared to the previously installed optics.

In addition, the UHV laser entrance port at the PLD chamber was replaced by an *intelligent* window, showing two unique features. First, it is able to keep the optical beam path clean for extended periods of time. A high-quality coated window mates to the large flange using a Viton O-ring. Inside the large flange is a large diameter, UV grade fused silica disc. An aperture

¹This work is supported by the Deutsche Forschungsgemeinschaft via SPP 1157 (GR 1132/13).

is positioned between the disc and the PLD target, limiting the portion of the disc coated by ablated material from inside the deposition chamber to a small section. This disc insures that the coated window is kept clean by intercepting the ablated plasma plume. Once the exposed section of the disc has become coated, the disc can be easily rotated exposing a new, optically clean surface, even during deposition. Second, an insertable mirror allows to determine the energy of the incoming excimer laser beam through a second installed window. For this purpose we use a pyroelectric detector head with a resolution of $3 \mu\text{J}$. Knowing the absorption factor, one can calculate the energy at the target. This *intelligent* window helps to improve the deposition capability by accurately monitoring one of the most critical parameters in the process: the on-target laser fluence. The properties of PLD-grown thin films depend strongly on this value, which may vary due to several factors in all PLD systems. On the one hand, the inner surface of the PLD chamber's laser entrance port is continuously covered by ablated material. On the other hand, the output of the excimer laser and the beam brightness can vary significantly depending on the lifetime of the laser gas fill, output coupler, and electrodes. Furthermore, the components of the optical path degrade with time due to color centers and/or degradation of reflecting or coated surfaces. Monitoring and adjusting the energy that actually enters the chamber before each run, or during the growth process, results in a constant on-target laser fluence and helps yield reproducible film properties and deposition rates.

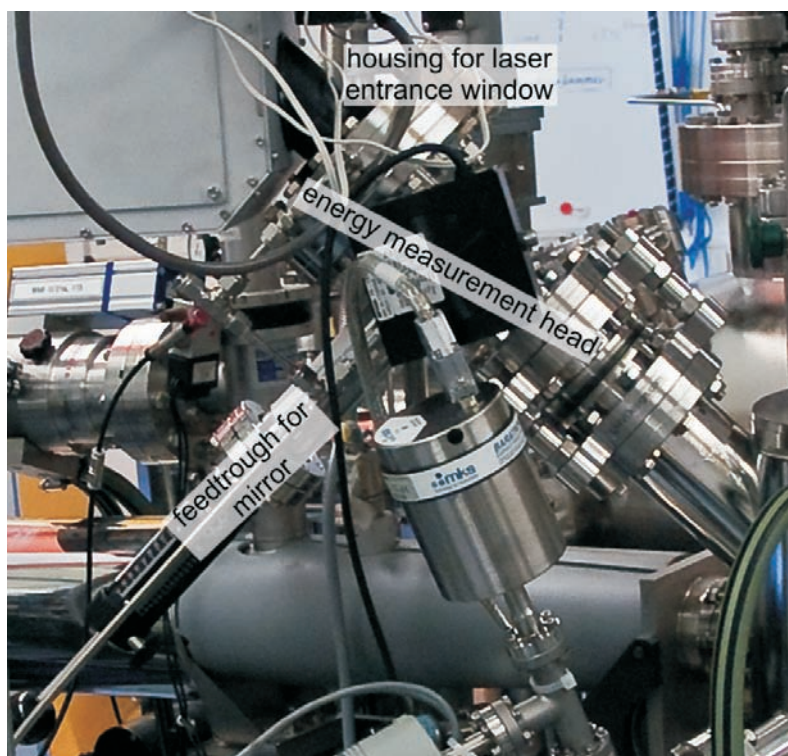


Figure 2: Laser entrance port (intelligent window) with energy detector head attached to the UHV laser-MBE cluster system.

target rotation, and target height. All these parameters are selected by the user at the PC from one single application window.

To use the full potential of the new laser beam optics, a new LabVIEW-based application has been developed for the PC which controls all the sensitive parameters of the laser-MBE system. For example, the software determines the energy of the excimer laser pulses in the PLD chamber, calculates the laser fluence at the PLD target, compares it to the value selected by the user, and then moves the lenses 1 to 3 to their appropriate positions. Moreover, the software controls the substrate temperature before, during, and after the deposition process, as well as target selection,

Crystal growth and study of the phase diagram of superconducting iron pnictides

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Superconductivity in FeAs-based materials is quite unexpected because most Fe-based compounds exhibit strong magnetic behavior. Therefore, the recent discovery of high temperature superconductivity in the iron pnictides [1] in the $ReO_{1-x}F_xFeAs$ (1111) family (Re = rare earth element) and later on in $Ba_{1-x}K_xFe_2As_2$ (122) and related compounds has attracted broad interest from researchers working in physics and chemistry. In particular, after transition temperatures T_c above 30 K were observed [2–4], an intense worldwide research activity started similar to that after the discovery of the cuprate superconductors [5]. Interestingly, it has been recognized early, that the new iron pnictide superconductors are characterized by a close proximity of magnetism and superconductivity [6, 7] similar to the superconducting cuprates.

Whenever a new class of superconducting materials is discovered, a key prerequisite is the development of clean single crystals, allowing to determine the intrinsic properties of these compounds. The initial stages to obtain single crystals of a new compound are basically always the same: Try to dissolve the compound into a solvent and lower the temperature so that the system becomes supersaturated and the desired compound crystallizes somewhere in the crucible. Very commonly used solvents in this approach are molten salts such as the eutectic mixture of NaCl and KCl or low melting metals like Sn, In, Bi, or Cd [8] and the recipes for crystal growth are very similar. In general, the same approach can be used for the single crystal growth of iron pnictides. However, due to the high vapor pressure of As at elevated temperatures here in addition a solvent allowing to lower the temperature for crystallization is needed. The high vapor pressure of As leads to strong complications in the whole handling and processing of the compound in general and in the growth of single crystals in particular. It does not only make the fabrication process complicated and thus time consuming, but also causes potential danger due to the necessity to work with toxic materials. Until today, already several accidents have been reported in laboratories working with the iron pnictides, which are partially owed to the eagerness of the involved crystal growers and physicists. However, with adequate precautions such as the use of glove boxes, closed ampoules and closed furnaces as well as exposing the final product to the open environment only at ambient temperatures, one can work safely with the FeAs systems.

- **$Ba_{1-x}K_xFe_2As_2$ (122) family:**

Among the novel iron pnictide superconductors currently under investigation, the 122-family has in some sense outstanding properties. Within this family, $Ba_{1-x}K_xFe_2As_2$ has the highest T_c and shows the highest critical magnetic fields. Moreover, it also forms a complete solid solution with the two isostructural mother compounds namely $BaFe_2As_2$ and KFe_2As_2 . Therefore, all mixtures crystallize in the same structure and basically the complete doping range of the 122 compounds can be probed using just one system.

The first crystals of the $Ba_{1-x}K_xFe_2As_2$ compound have again been successfully grown by making use of the well-known flux method based on different low melting metals as a solvent. This, in fact, has led to a remarkably fast success in obtaining single crystals of this compound, especially when Sn was used as a solvent. This growth technique, which was also applied by our group according to the basic recipe of Canfield [9] in the initial attempts, led to platelet

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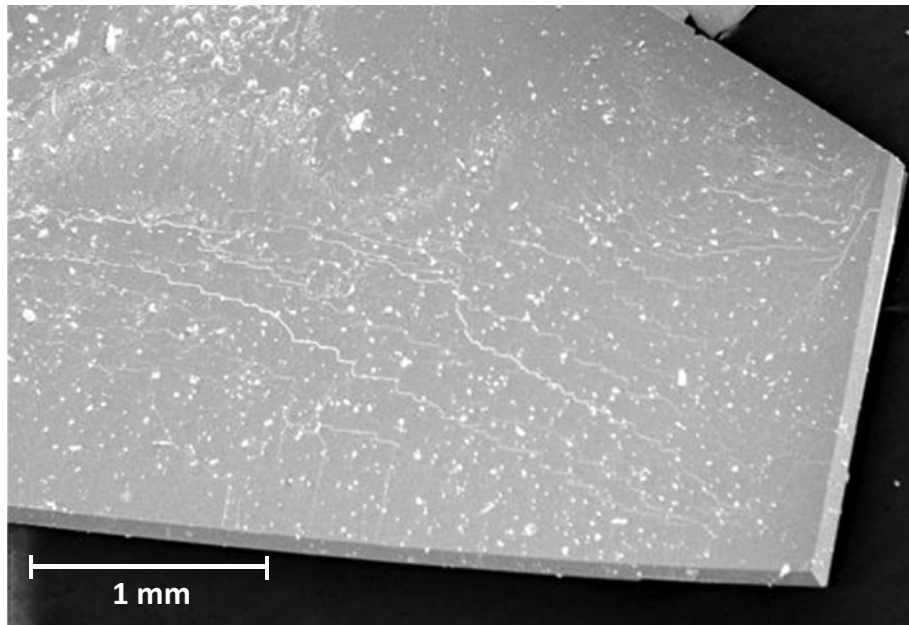


Figure 1: SEM micrograph of a $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ single crystal grown from a Sn flux. The platelet like crystal shows well developed outer surfaces and edges. The c -axis is oriented perpendicular to the platelets. Upon increasing the doping level by increasing the K content [3], the surfaces are less well developed. Due to the layered structure of the 122-compound, the dimension parallel to the c -axis is the smallest.

like single crystals with a lateral size of several mm, showing well defined surfaces and corners. Figure 1 shows such a typical example of a $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ single crystal grown at the WMI in a Sn flux. Although the achieved crystals were looking nice, it soon became clear that the crystals obtained by using Sn or other metal fluxes strongly suffer from the incorporation of considerable amounts of the flux metals into their structure. For the crystals grown in Sn flux one typically finds about 1 at.% of Sn incorporated in the crystals structure after growth. This high impurity concentration is expected to strongly affect the physical properties of the obtained crystals. The crystals, especially those with low K-doping showed good crystallinity with well developed surfaces and sharp edges. Moreover, we obtained clear Laue patterns for these crystals. Upon going to higher K-doping, the obtained crystals showed a tendency to spontaneous exfoliation and cleavage. Some of the obtained crystals with higher K-doping also appeared as bent platelets, which started to cleave at the corners as can be seen from Fig. 2. For such crystals also the Laue images showed reflections which were faint and smeared out. Resistivity vs. temperature measurements on different crystals with the same nominal doping showed different behavior, depending on the detailed position of the electrical contacts on the sample surface and whether cleaved or uncleaved crystals were used.

At this point we obviously became concerned about the homogeneity of our single crystals and therefore refrained from distributing them around to many places. To control the homogeneity of these crystals we deliberately performed a cleaving in a way that many terraces in different depths of the crystal along the c -axis direction were obtained. An example is shown in Fig. 3. On such terraces we performed EDX measurements to determine the variation of the K-content in c -axis direction. What we found was a pronounced gradient in the K-content along the c -axis going from the center to the surface of the grown crystal. While on the surface of the $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ crystal (measuring positions 1 and 2 in Fig. 3) we measured a K-concentration of $x = 0.49$, the center of the crystal shows x -values as low as 0.19 were obtained. Notably, on one and the same terrace the x was found constant within the error of the analysis.

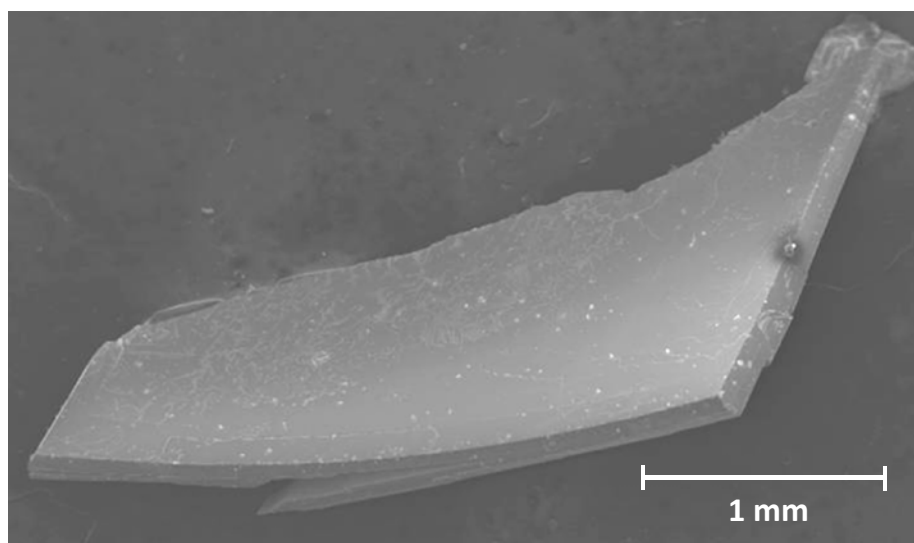


Figure 2: Bent crystal of $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ with a nominal K-doping of $x = 0.4$. Crystals with higher K-doping tend to be bent due to internal stress. This internal stress is induced by the nonuniform concentration of the K-dopant over the crystal as a direct consequence of the thermodynamic phase diagram.

We note that such strong variations in composition are a direct consequence of the compositional phase diagram of a solid solution system with large differences in the atomic radii of the atoms. Hence, the use of a crucible growth process to achieve single crystals of the iron pnictide compounds is a severe shortcoming. Evidently, the strong concentration gradient also explains quite naturally the strong bending of the crystal platelets and their tendency to cleave spontaneously. The reason for that is the large internal strain introduced by the strong K-gradient. Furthermore, the use of such crystals for bulk measurements may easily explain the reported coexistence of superconductivity and magnetic order in such samples. We note, however, that even such inhomogeneous samples may be used in experiments applying surface sensitive methods with only small probing depth. Obviously, in such experiments then the K-content for each measuring spot on a particular cleavage layer has to be determined separately. For the electron-doped compound $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ in principle the same applies with respect to sample homogeneity. However, here the distribution coefficient seems to be closer to unity and therefore the crystals are more homogeneous. Nevertheless, the crystal growth in crucibles using self-fluxes leads to samples, which should be referred to as being rather melt-textured samples than real single crystals. Furthermore, at this point in time it is certainly necessary to apply different growth techniques instead of simple crucible growth which lead to optimum sample quality as soon as possible.

The “silver bullet” for the inhomogeneity problem in solid solution crystals with distribution coefficients differing strongly from unity is of course the application of the traveling zone (TZ) method for congruently melting compounds or the traveling solvent floating zone method (TSFZ) for incongruently melting compounds or materials where it becomes important that the growth temperature needs to be reduced by the use of a lower melting flux. For the $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ compound the use of the TSFZ method would in fact be the ideal solution for the production of big homogeneous single crystals as it already has been in the case of the 214 class crystals of the cuprates. The main obstacle here is the evaporation of both As and K. Therefore, it is very likely that high pressure techniques have to be applied. In such an experimental approach heating can either be realized using light in an mirror furnace or, alternatively, by high frequency heating since these compounds are relatively good conductors.

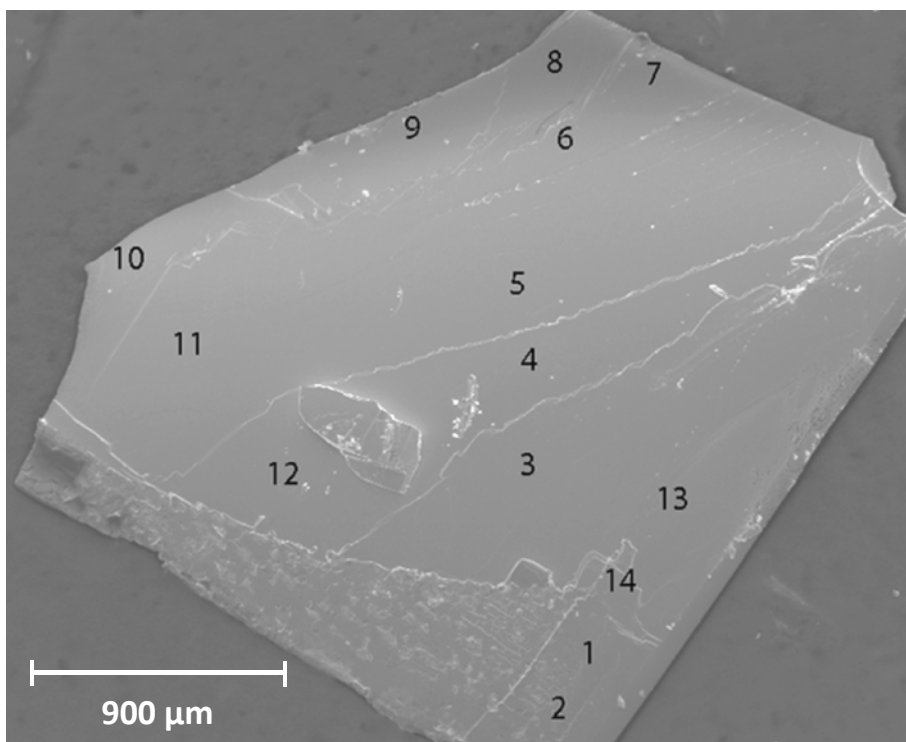


Figure 3: Cleaved Ba_{1-x}K_xFe₂As₂ crystal with a nominal K-content of $x=0.5$. EDX measurements were performed at different positions corresponding to a different depth in c -axis direction of the crystal. While the pairs of measuring spots on the same terrace, i.e. same depth along the c -axis (5,11; 12,4; 10,8; 1,2;) showed a homogenous distribution within the accuracy of the measurement, the K-content varied from $x=0.49$ on the surface of the crystal to $x=0.19$ in the innermost parts.

If the evaporation problem cannot be solved by applying gas pressure alone, the use of metal or ceramic container sheets around the molten bar would be an alternative. The disadvantage of the use of such a sheet would be the loss of direct optical observation of the molten zone. These growth experiments are under way using a high frequency heated high pressure furnace with maximum pressure of up to 30 bar.

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Graphite oxide modification and colloid formation

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Graphite oxide (GO) has been prepared in 1860 by Brodie [1]. Over the years various applications have been discussed: as the positive electrode in lithium cells [2–4] for the fabrication of membranes [5–8], as novel composites in which GO is back-reduced to graphite [9, 10] and carbon-coated nanoparticles [11, 12]. Only recently it has received great attention as the precursor of functionalized graphene layers [13, 14]. Considering the wide range of potential applications, precise knowledge of the structure of GO is essential. In 1998 Lerf et al. [15] proposed a new structural model based on solid-state nuclear magnetic resonance experiments, assuming the existence of epoxy groups (as proposed by Hofmann [16], instead of ether functions) in addition to hydroxyl groups (see Fig. 1). These authors assumed that there are two kinds of regions in the graphite oxide: aromatic regions with π -bonded six-rings and regions made up of aliphatic six-rings. The carbon layers are therefore slightly bent and warped in the regions containing sp^3 orbitals, but flat in the region bonded with sp^2 orbitals. This model is now well confirmed by molecular simulation [17] and chemical modification of the oxygen functions [18, 19].

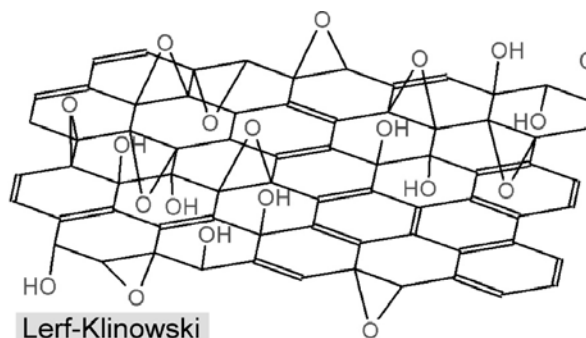


Figure 1: The structural model of graphite oxide as proposed by Lerf et al. [15]. Figure taken from [21]

The chemical modification of GO, especially the epoxide functions, can be accompanied with more severe structural changes. In ref. [15] it has been shown that treatment of GO with iodide or heating it up to 100 °C in vacuum lead to a partial or complete disappearance of the epoxide functions. Simultaneously, the hydroxyl functions have been transformed to phenolic groups via breaking C-C single bonds shifting the NMR peaks towards 110 ppm and 150 ppm, respectively. A proposed mechanism of this rearrangement after loss of epoxide oxygen is shown in Fig. 2.

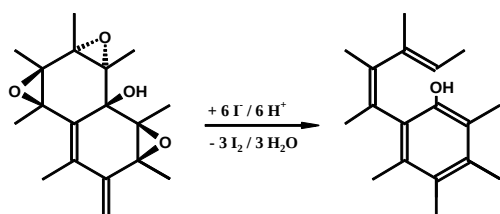


Figure 2: Rearrangement of the bonding system after loss of epoxide oxygen (taken from Ref. [15])

At a peculiar level of bond-breaking hydroquinone groups should appear which can be oxidized easily to quinone, and that is the main structural feature of Boehm's GO model [20]. The GO sample of Szabo et al. [21] seems to be the final product of this process. The preparation of this sample has been carried out with repeated oxidation of the GO obtained and it is reasonable to assume that the epoxide groups are attacked considerably and destroyed to some extent. This extent in-

creases with the number of reaction cycles during the repeated oxidation, washing and drying processes.

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Starting from this result one can envisage that the other models of graphite oxide structures could be considered also as different states of GO obtained under slightly varying preparation conditions and sample treatments. Thus it seems to be meaningful to elucidate reaction pathways which could lead to the different states (i.e. structural models). The best way to induce structural transformations of GO is to attack the highly reactive epoxide functions. Apart from thermal treatment (see [15]) the epoxy groups can be attacked by electrophilic agents like protons or nucleophilic agents like the OH^- ions. For the first type of reaction concentrated sulfuric acid has been used. Neither at room temperature nor at 65°C we observed any sign of a reaction by means of ^{13}C CP-MAS-NMR spectroscopy. Treatment of GO with 0.01 M NaOH is normally used to obtain a highly stable colloidal dispersion of solid GO [8]. Under this condition GO is stable and even the dispersions remain stable for a week or more. Heating of a GO suspension in 1 M NaOH up to 60°C for several days leads to a strong color change from yellowish brown to black, but only to minor changes in the NMR spectrum.

Only after treating GO with 8 M KOH at 90°C (some minutes) a strong deoxygenation is observed [22]. The corresponding NMR spectrum looks very similar to that observed for the iodide treated GO. Because of the high reaction temperature we assume that the deoxygenation is mostly an effect of the temperature applied. The highly concentrated KOH solution may have enhanced the reaction rate, probably due to the formation of phenolate instead of phenol. One should mention also that the starting material used by these authors show also some hints of destruction. Considering this result one cannot rule out that the trials of Boehm et al. [23] to determine the number of functional groups by treating GO samples with various types of bases lead to some structural modification of GO and the creation of new acidic sites by the reagents applied.

An important intermediate step in the deposition of graphene films is the formation of colloidal dispersions of GO. Whereas a colloidal dispersion of GO is obtained during work up of the GO preparation easily, it is rather difficult to get mono-disperse and stable dispersions in larger quantities. In addition, the colloidal dispersions are not well characterized up to now.

Trials to replace time consuming work up processes by dialysis were only partially successful, since we could not wash out manganese dioxide completely which is formed during oxidation of graphite with potassium permanganate (Hummers-Offemann method [24]). Since the manganese oxide does not appear as a separate phase in scanning electron microscopic images and microprobe analysis and since we do not get a clearly defined layer distance for the graphite oxide the manganese dioxide could be located still in the interlayer space of the GO or the MnO_2 nanoparticles are completely covered by the GO layers comparable with the situation in Ref. [11, 12]. To remove the MnO_2 the GO raw material has been treated with 2 M hydrochloric acid for two days. We refrained from adding hydrogen peroxide to speed up the reaction rate because there is some hint for a back reduction of GO with this reagent.

The finest particles form a colloidal dispersion during the workup of GO. A concentration of GO nanoparticles of about 1 mg/ml is reached easily in this way. Larger particles which precipitate within hours or a day can redispersed easily in 0.01 M NaOH. In such colloidal dispersions concentrations of up to 3mg/ml can be found. Dispersions in NaOH are more stable than in pure water (see above). The degree of dispersion can be strongly enhanced by application of ultrasound or mechanical dispersing (based on the rotor/stator principle). In addition, the stability of the dispersions so obtained is strongly enhanced, probably due to a narrower particle size distribution. The most stable dispersion has been obtained in the organic solvent dimethylsulfoxide DMSO, but the GO is transferred back to a graphite-like material without adding external reducing agents. This latter dispersion seems to be an excellent starting point for forming graphene films. Experiments towards this direction are underway.

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Novel design of the condensation stage of a cryogen-free dilution refrigerator

Kurt Uhlig

Introduction

For most ultra-low temperature applications, cryogen free ("dry") dilution refrigerators (DRs) have become the best choice among cryocoolers available in recent years. They are easy to operate, economical and can be completely computer-controlled. Generally, they offer a considerably larger experimental space than traditional cryostats with liquid helium pre-cooling. Cryogen free DRs can be operated in a wide temperature range for experiments from 1 K to below 10 mK. They are applied in areas like solid state physics, materials research, quantum computer science, opto-mechanics, or astrophysics, just to name a few [1].

Quite a number of commercial companies offer dry DRs these days [2], ranging from small top-loading cryostats [3] to cryostats with high cooling capacities of up to 1.5 mW at a temperature of the mixing chamber of 120 mK [4]. Right now, approximately 75 % of newly sold DRs are dry cryostats!

In our original cryostat, and in almost all commercial models available, the ^3He flow is cooled in three major components to its lowest temperature of about 10 mK, with the first cooling stage being a two-stage pulse tube cryocooler, the second stage an intermediate stage and the third stage a dilution refrigeration unit (Fig. 1). The intermediate stage is made from a flow restriction and a heat exchanger which makes use of the cold ^3He gas pumped from the still to cool the back-streaming ^3He ; it is similar to a Joule-Thomson stage. Although the intermediate cooling stage can be left out altogether, it is very desirable when a high cooling power of the still is required to heat sink a big radiation shield and coaxial and other electric cables. Here, we present a redesigned heat exchanger of the intermediate stage which was made mostly from copper screens; construction details and performance data of the heat exchanger are described. The heat exchanger is shorter than its predecessors, allowing for a more compact construction of the cryostat.

The first cooling stage in a dry DR always consists of a two-stage pulse tube refrigerator (PTR) which cools the ^3He of the dilution circuit at its first stage to about 50 K; in a second heat exchanger which is attached to the second regenerator, the ^3He flow is cooled to a temperature below 10 K [5–7], and finally the ^3He is cooled to a typical temperature of 2.5 K which is the temperature of the second stage T_{PT2} of the PTR [8]. T_{PT2} can be higher (up to 4 K or 5 K),

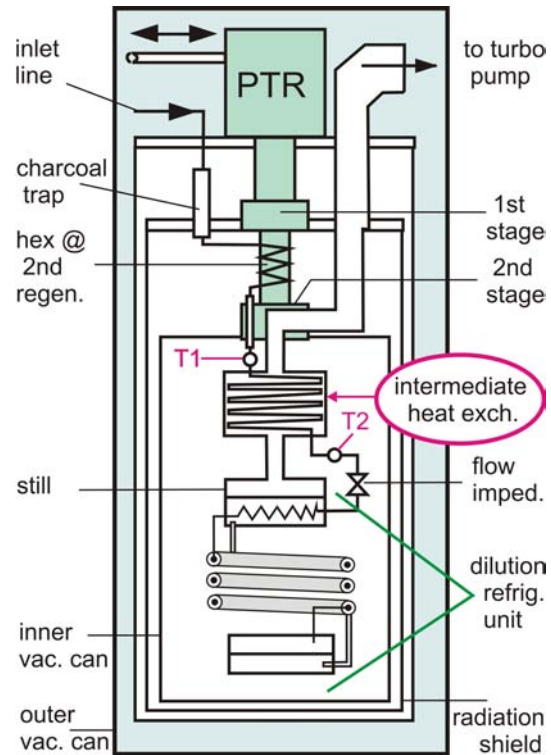


Figure 1: Sketch of a dry DR. It consists of a two-stage pulse tube refrigerator, a dilution refrigeration unit and the intermediate stage described below.

depending on the thermal load to the PTR. Next, the ^3He is cooled in a heat exchanger to a temperature below 1 K (Fig. 1). This heat exchanger is placed between the still of the DR and the second stage of the PTR and transfers the heat of the back-streaming ^3He to the ^3He pumped from the still. In our paper we will present a new method to construct this heat exchanger. The efficiency of the heat exchanger will be shown in a ^3He enthalpy diagram.

Construction of the intermediate heat exchanger

The new version of our heat exchanger is made from disks of copper screen (Fig. 2). Ten disks (57 mm dia., 50 mesh) are separated from each other by plastic spacers (47 mm inner diameter). A CuNi capillary (0.8 mm inner diameter) is soft soldered to the disks; the ^3He return gas flows through this capillary and is cooled in 10 steps by the copper screens which are situated in the cold gas stream flowing out of the still of the DR. Copper disks and spacers are bolted together to form a cartridge that fits snugly into a thin walled stainless steel housing. The relatively wide diameter of the copper screens was chosen so that the pressure drop along the heat exchanger was negligible. The gas pressure in the screen heat exchanger is low (on the order of 10 Pa), and sizable pressure increases at the inlet of the heat exchanger due to the flow of ^3He cannot be tolerated as they would result in an increase of the still temperature. The idea of using screens was to make sure that the flow of gas was uniform throughout the heat exchanger and to avoid holes and gaps where the gas would flow without exchanging heat. Only one type of screening has been tested, so far. One could vary the number of screens and the mesh size to find the optimal heat exchanger configuration. Thermometers were placed at the inlet and outlet of the heat exchanger in the return line to get quantitative information on the heat transfer (T_1 and T_2 in Fig. 1). A separate pressure line was installed in the cryostat to measure the inlet pressure of the ^3He flow.

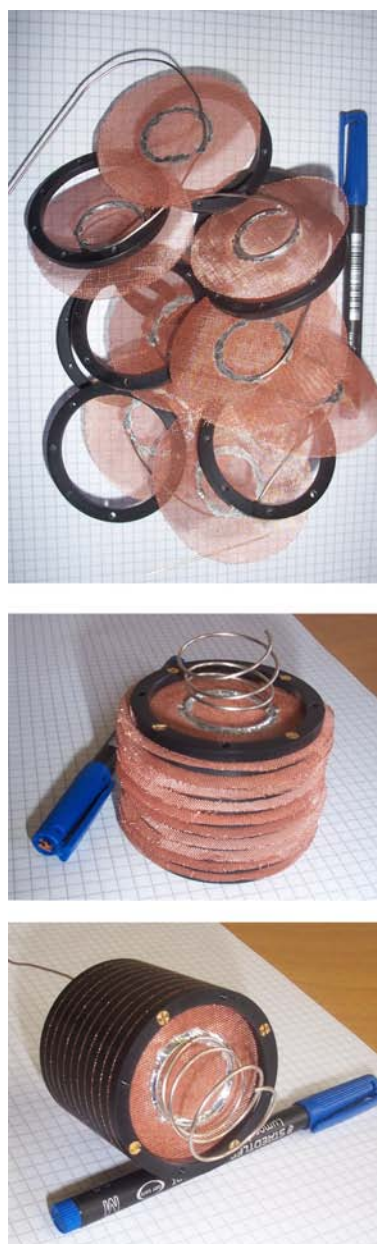


Figure 2: Copper screens with spacers after soft soldering the inlet line to the screens (top). Copper screens and spacers have been stacked and bolted together (center). Same stack, machined to form a cartridge which fits into the outer tube of the heat exchanger (bottom).

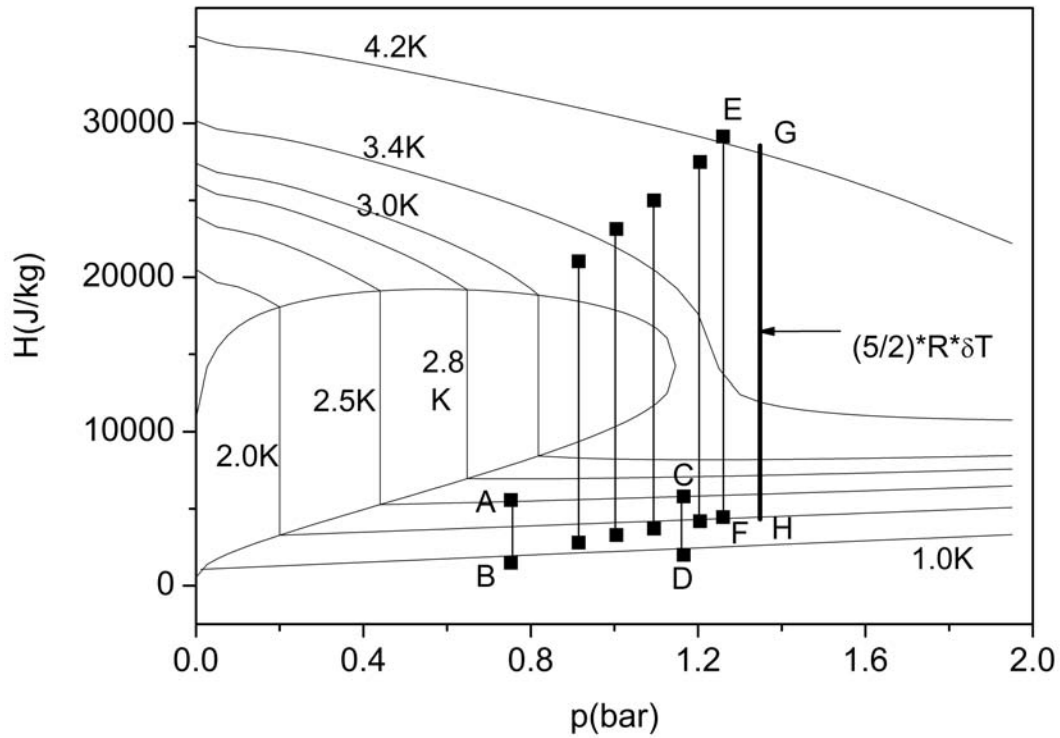


Figure 3: Enthalpy-pressure diagram of ^3He . Several examples of the cooling process in the intermediate heat exchanger are shown.

Performance of the intermediate heat exchanger

In Fig. 3, the low temperature enthalpy-pressure diagram of ^3He is depicted [9]. In a first example, the ^3He flow is liquefied and pre-cooled at a pressure of 0.75 bar to a temperature of 2.5 K by the PTR (point "A" in Fig. 3); 2.5 K is also the base temperature of our PTR. Only the small amount of 3900 J/kg is necessary to cool the ^3He to the temperature of the still of 0.75 K (point "B"), whereas a much larger enthalpy difference of $\delta H = (5/2) \times R \times (T_A - T_B)$ of 1.2×10^4 J/kg would be available at the low pressure side of the heat exchanger ($T_A = 2.5$ K; $T_B = T_{\text{still}} = 0.75$ K) [7]. A similar situation is obtained for a higher inlet pressure of 1.15 bar (points "C, D"). As the enthalpy difference at the low pressure side exceeds the enthalpy required at the high pressure side of the heat exchanger by a wide margin, we cannot really assess the quality of the heat exchanger for this experimental condition.

In order to test better the enthalpy transfer in the heat exchanger, the temperature of the ^3He at the inlet of the heat exchanger was upped by heating the second stage of the PTR. At point "E" in Fig. 3, the ^3He stream is cooled to 4.25 K at a pressure of 1.25 bar; when the ^3He leaves the heat exchanger, its temperature has been reduced to 2.0 K. The amount of enthalpy removed from the stream is 2.49×10^4 J/kg, whereas we find that an enthalpy δH of 2.42×10^4 J/kg is available on the low pressure side ("G, H" in Fig. 3). Thus, in the example given here, the enthalpy transfer is complete within our experimental accuracy.

It would be interesting to increase the inlet temperature further to find the limitations of the heat transfer and from there to optimize the geometry of the heat exchanger. A small fraction (<5 %) of ^4He in the circulating gas of the DR has been ignored in the calculation.

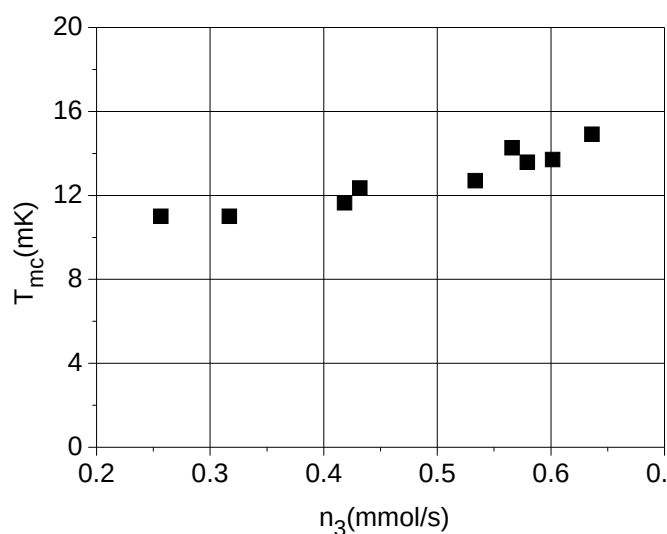


Figure 4: Temperature of the mixing chamber as a function of the ^3He flow.

Operation of the DR and summary

In Fig. 4, we give the temperature of the mixing chamber as a function of the ^3He flow. We used one of our standard dilution units in the experiments; it had a concentric tube heat exchanger and two small discrete heat exchangers. For thermometry, ruthenium-oxide resistance thermometers were available which were made and calibrated at our lab. They were placed in the liquid $^3,^4\text{He}$ mixture inside the mixing chamber. Base temperatures varied between 11 mK and 15 mK, depending on the ^3He flow rate.

In summary, the report describes the design of a heat exchanger for the intermediate stage of a DR. Heretofore, the heat exchanger was usually made from a structure of capillaries, whereas in the new design it was made from a stack of copper screens. The new setup has a low flow impedance and its construction is shorter than with previous designs, allowing for a shorter construction of the cryostat overall. It is advantageous to have the intermediate heat exchanger in a DR when the second stage of the PTR is exposed to a high heat load, or when high refrigeration capacities are required at the still. The heat exchanger has not been optimized, yet. The diameter and the number of screens, the screen size and the distance of the screens in the stack are parameters that could be tuned to the ^3He flow of the DR. Another option would be to integrate the heat exchanger into the housing of the still and thereby reduce the total length of the dilution unit even more.

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Experimental Facilities and Infrastructure

In the following basic information on the key experimental facilities and components of the technical infrastructure installed at the Walther-Meißner-Institute (WMI) is given.

UHV-Laser-MBE

The WMI operates a UHV-Laser-Molecular Beam Epitaxy (L-MBE) system for the growth of complex oxide heterostructures. The system has been designed to meet the special requirements of oxide epitaxy. The UHV cluster tool consists of the following main components:

- central transfer chamber;
- load-lock chamber with heater system for substrate annealing;
- laser deposition chamber with in-situ reflection high energy electron diffraction (RHEED) system, laser substrate heating system, and atomic oxygen/nitrogen source, the RHEED system has been modified to allow for the operation at high oxygen partial pressure up to 0.5 mbar;
- surface characterization chamber with UHV scanning force microscope (Omicron);
- metallization chamber with a four heart electron gun system and a liquid nitrogen cooled sample stage. The sample holder can be tilt for shadow evaporation;
- KrF excimer laser.

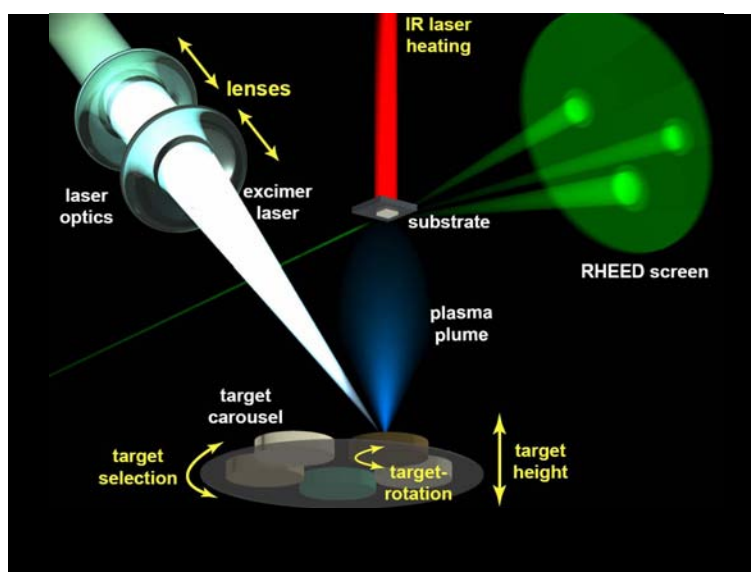
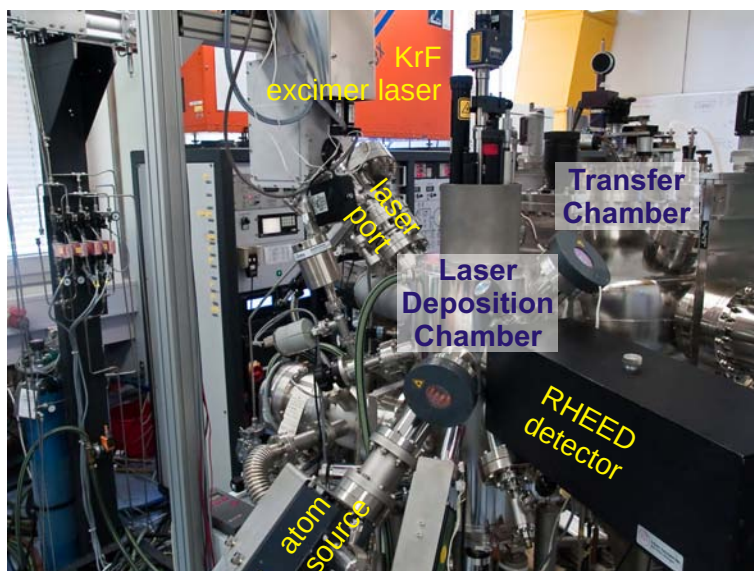


Figure 1: Top: UHV-Laser-Molecular Beam Epitaxy System. Bottom: Principle of the deposition process.

The system is used for the growth of complex oxide heterostructures consisting of superconducting, magnetic, dielectric, and semiconducting materials such as the high-temperature superconductors, the doped manganites, the double perovskites, magnetite, zinc oxide, etc..

The original laser molecular beam epitaxy system (laser-MBE) designed already in 1995/96 until now has been permanently upgraded and modified. In particular, the substrate heating system and the temperature control unit was changed from a resistive radiation heater to an infrared laser heating system (see Fig. 3, left) including a pyrometer for determining the sample temperature. In addition, a source for atomic oxygen and nitrogen has been added. The main advantage of the new heating system is that only the substrate is heated while the surrounding parts are hardly affected (Fig. 3, right). In this way one can achieve an essentially better vacuum at temperatures well above 1000°C. The achievable substrate temperature is limited by the melting point and the size of the substrate material (approx. 1410°C for a $5 \times 5 \text{ mm}^2$ silicon substrate). The laser heating system has already been successfully used for removing the amorphous silicon oxide layer from the surface of silicon substrates at 1150°C. This is required for the epitaxial growth of oxide thin films on this substrate.

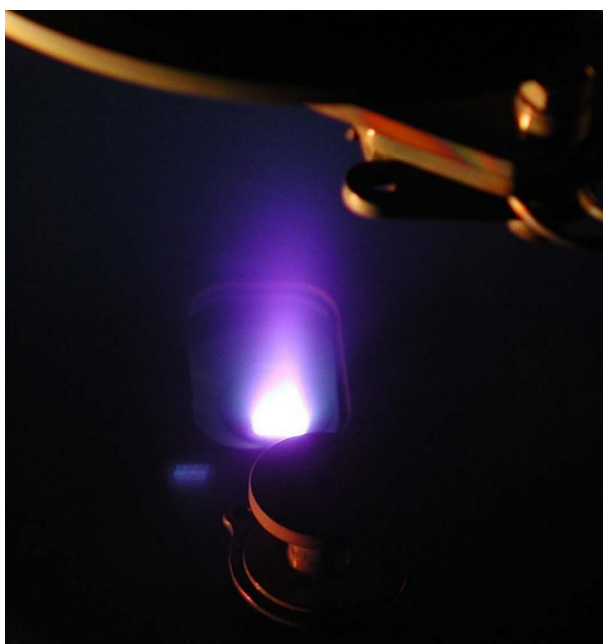


Figure 2: Pulsed Laser Deposition (PLD): When the pulse of the UV laser (KrF excimer laser, 248 nm) hits the target, the target material is ablated and the so-called laser “plume” containing highly excited atoms and molecules is formed.

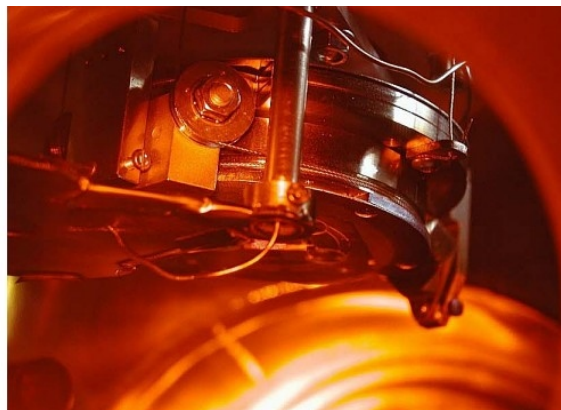
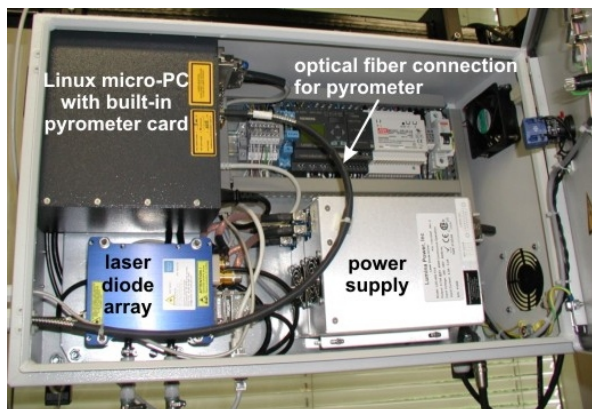


Figure 3: Components of the laser heating system: The substrate is heated using an IR diode laser head that is located in a separate box far away from the deposition chamber (left). The laser light is brought to the substrate (right) via an optical fiber.

Single Crystal Growth and Synthesis of Bulk Materials

Transition metal oxides are of great interest due to their various interesting physical properties (e.g. high temperature superconductivity, colossal magnetoresistance, ferroelectricity, nonlinear optical properties etc.) and their high potential for applications. Therefore, the WMI operates a laboratory for the synthesis of bulk materials and single crystals of transition metal oxides. Besides various chamber- and tube furnaces a four-mirror image furnace is used in the crystal growth of various oxide systems. With this furnace crystals of many different compounds of the high temperature superconductors and various other transition metal oxides have been grown as single crystals using the traveling solvent floating zone technique. The furnace consists basically of 4 elliptical mirrors with a common focus on the sample rod and with halogen lamps in their other focus. By irradiation of the focused light the sample rod is locally heated and eventually molten. The molten zone can be moved up and down along the entire sample rod under simultaneous rotation. Due to the anisotropic growth velocity a preferential growth of those grains with the fastest growth velocity along the pulling direction is obtained and the formerly polycrystalline rod is transformed into a single crystal. Single crystal growth can be performed with this furnace at maximum temperatures up to 2200°C in the pressure range from 10^{-5} mbar up to 10 bar and in oxidizing, reducing as well as inert atmosphere.



Figure 4: The four-mirror image furnace installed at the crystal laboratory of the WMI. Crystals can be grown by the floating zone and traveling solvent floating zone technique at temperatures up to 2200°C and pressures up to 10 bar.

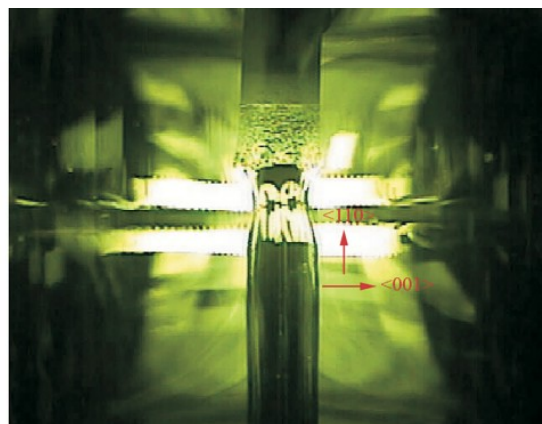
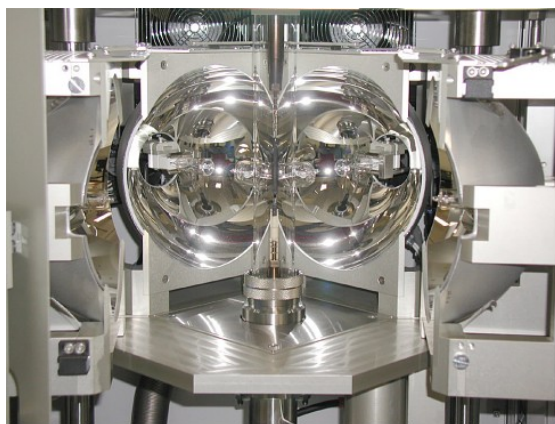


Figure 5: Left: Central part of the image furnace with the four elliptical mirrors. In the center one can see the quartz tube with the poly-crystalline rod. Right: View on the molten zone of $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$ (melting point: 1280°C) obtained by a CCD camera.

The X-ray diffraction systems

For x-ray analysis the Walther-Meissner-Institute operates two X-ray diffractometers (Bruker D8 Advance and D8 Discover). The two-circle system is used for powder diffraction. In this system the samples can be heated in oxygen atmosphere up to 1600°C. It is equipped with a Göbel mirror and an area detector to save measuring time. The second system is a high resolution four-circle diffractometer that can be used for reciprocal space mappings. It is equipped with a Göbel mirror and an asymmetric two-fold monochromator and allows for the texture analysis of thin film superlattices and single crystalline materials. In both systems measurements can be carried out fully computer controlled.

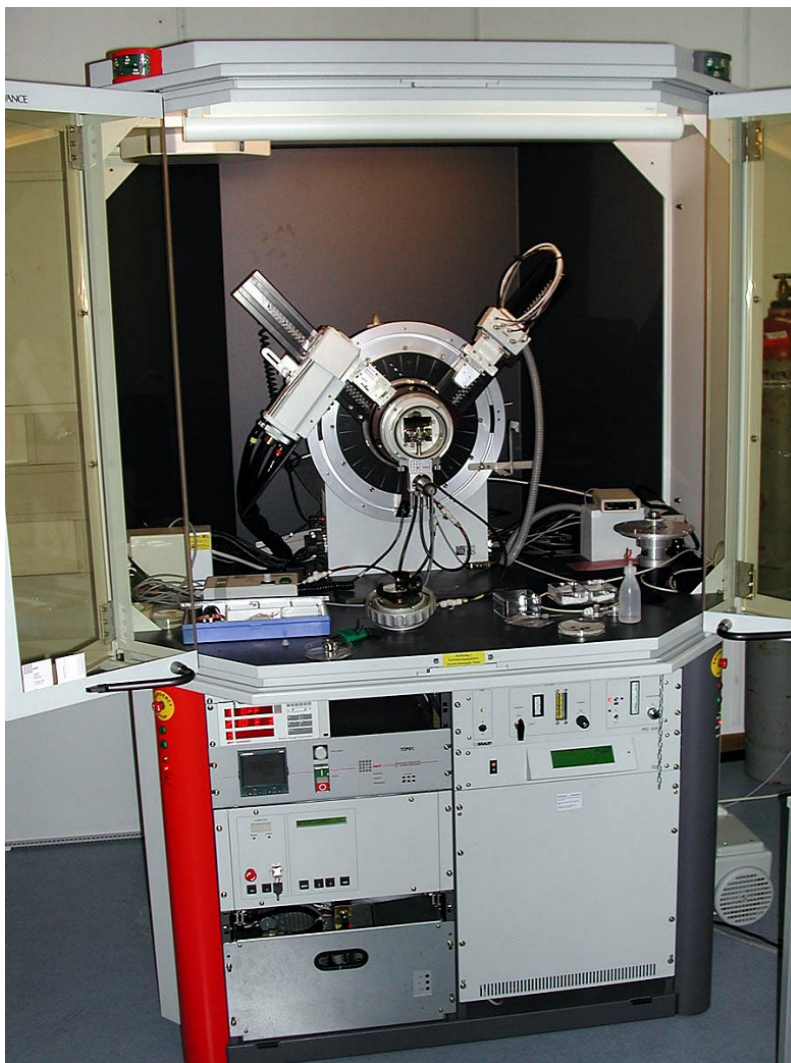


Figure 6: The two-circle X-ray diffractometer Bruker D8 Advance.

Beyond these two Bruker x-ray systems a Laue camera for single crystal analysis and a Debye-Scherrer camera are available.

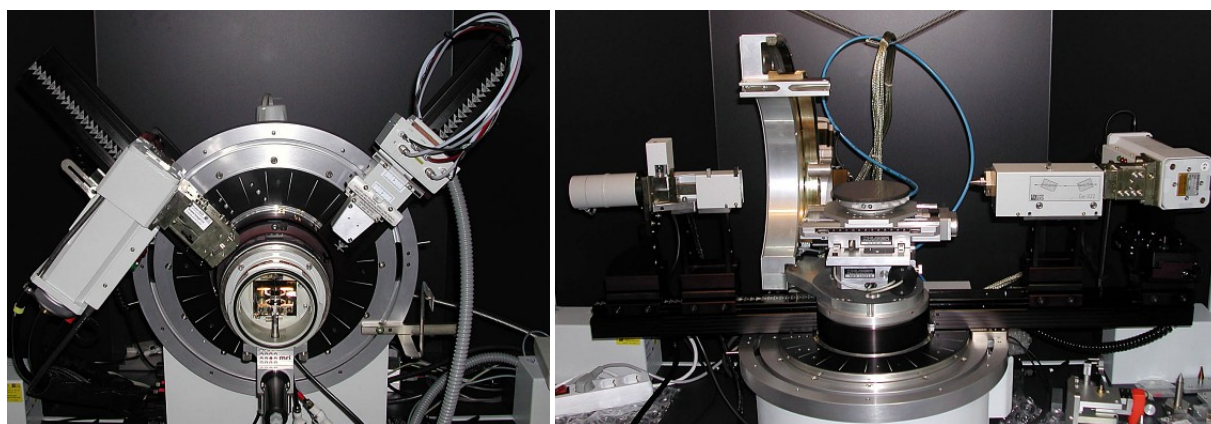


Figure 7: Left: High temperature sample holder of the D8 Advance system. Right: Four-circle high resolution X-ray diffractometer Bruker D8 Discover.



Figure 8: Quantum Design SQUID magnetometer.

The SQUID-magnetometer

For the analysis of the magnetic properties of materials, a Quantum Design SQUID magnetometer system as shown in Fig. 8 is used at the WMI. The SQUID magnetometer allows for measurements in the temperature regime from 1.5 to 400 K and provides excellent sensitivity particularly in the low field regime. Due to the excellent sensitivity of the system, thin film samples with a very small sample volume can be analyzed. In a special inset, samples can be measured up to temperatures well above room temperature (up to 500°C). For this option the sample volume has to be reduced.

The SQUID magnetometer is equipped with a superconducting solenoid allowing for a maximum field of 7 T. At present, the magnetometer is used for the characterization of magnetic materials (both in bulk and thin film form). Examples are the doped manganites, magnetite, the double perovskites, magnetic semiconductors, or multiferroics.

The High Field Laboratory

Transport and thermodynamic properties of samples are often studied as a function of applied magnetic field. For such measurements several superconducting magnets are available at the WMI. Two of them (8/10 and 15/17 Tesla magnet system) are located in the high magnetic field laboratory in the basement of the WMI. The magnet systems are lowered below the ground level to facilitate the access

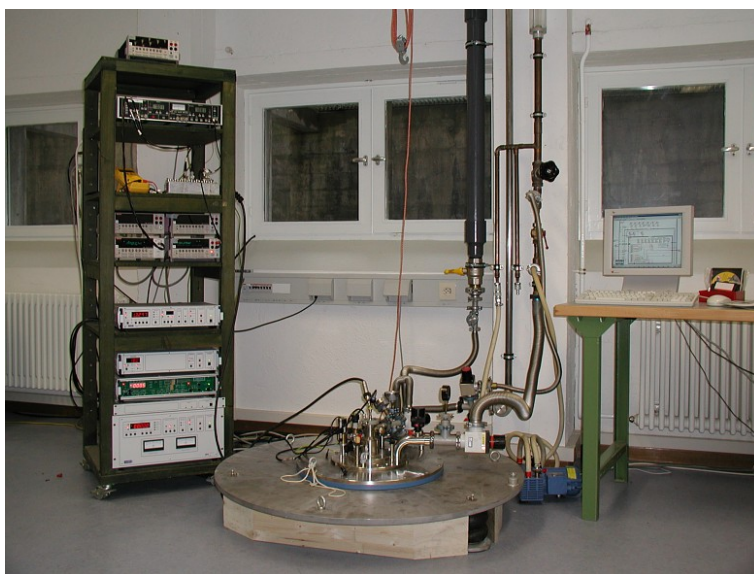


Figure 9: High field laboratory with Oxford 17 T magnet system.

to the top flange and the change of the sample sticks. The magnet systems are decoupled from the building to avoid noise due to mechanical vibrations. A variety of sample holders can be mounted allowing for e.g. sample rotation during the measurement. For standard sample holders the accessible temperature regime is $1.5 \text{ K} < T < 300 \text{ K}$. However, also $^3\text{He}/^4\text{He}$ dilution refrigerator inserts ($T > 20 \text{ mK}$) or high temperature units ($T < 700 \text{ K}$) can be mounted. All measurements are fully computer controlled (by the use of the LabView software tool) allowing for remote control and almost continuous measurements.



Figure 10: Top: Part of the clean room facility with optical lithography equipment and clean room benches. Bottom: Resist coater and hot plates.

The Clean Room Facility

For the fabrication of nanostructures and superconducting as well as spintronic devices the WMI operates a class 1000 clean room facility with an area of about 50 m². This clean room facility has been put into operation at the WMI within the year 2001. The clean room is subdivided into two parts for optical lithography and electron beam lithography, respectively. The clean room facility is equipped with the standard tools for optical lithography such as resist coaters, hot plates, wet benches, a Karl Süss MJB3 mask aligner and an optical projection lithography system. The technical infrastructure for the clean room is located in the basement of the WMI directly below the clean room area.

Since 2005 the clean room also is equipped with a reactive ion etching system, Plasmalab 80 Plus with ICP plasma source (Oxford Instruments Plasma Technology).

Electron Beam Lithography

The Electron Beam Lithography System is installed in one part of the clean room facility. It consists of a Philips XL 30 SFEG scanning electron microscope (SEM) with a Raith Elphy Plus electron beam lithography system and a laser interferometer table for precise stitching of writing fields.

The SEM is equipped with a hot field emitter and typically provides a beam diameter of less than 1.5 nm at ≥ 10 keV or about 2.5 nm at 1 keV. The lithography unit allows the fabrication of nanostructures down to about 10 nm. We have realized the controlled fabrication of metallic strip patterns with a strip width of about 20 nm. The electron beam lithography is used for the fabrication of nanostructures in metallic and oxide systems required for the study of quantum effects in mesoscopic samples.

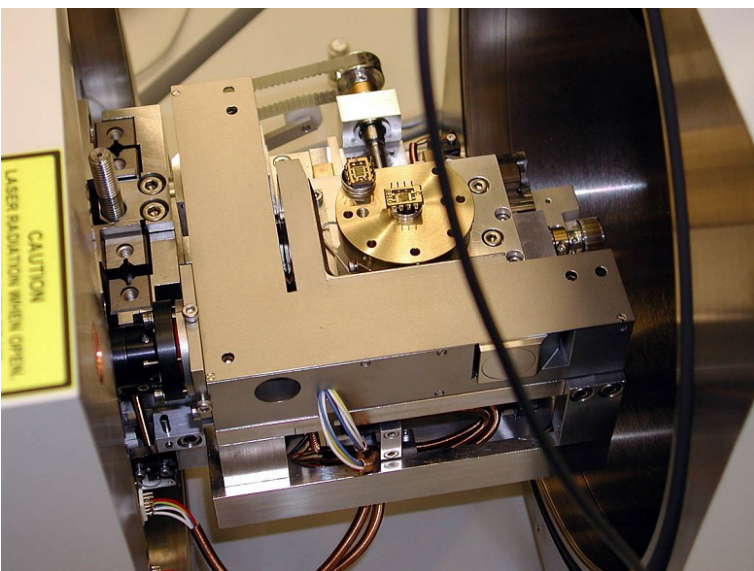
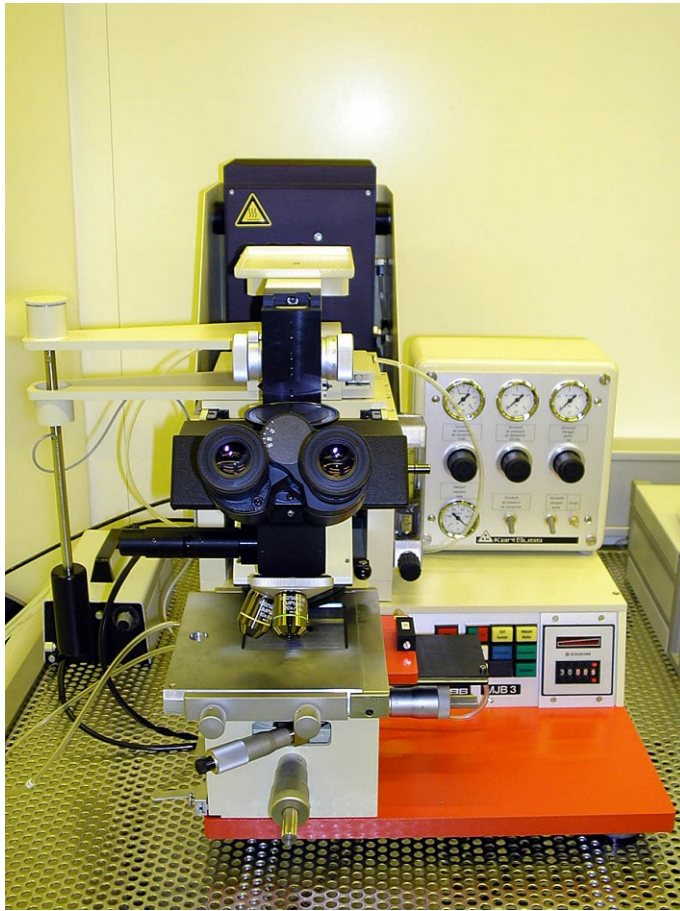


Figure 11: Top: Philips XL 30 SFEG Scanning Electron Microscope with Raith Elphy Plus Lithography System. Bottom: Raith Laser Stage.



Optical Lithography

For optical lithography a Karl Süss MJB 3 maskaligner or an optical microscope based projection system are used. The maskaligner is operating in the 1 : 1 soft or hard contact mode and is using chromium metal masks. In the projection system the mask pattern is demagnified by a factor of 5 to 100. Therefore, cheap foil masks can be used. With both systems microstructures with a lateral dimension down to $1\mu\text{m}$ can be fabricated.

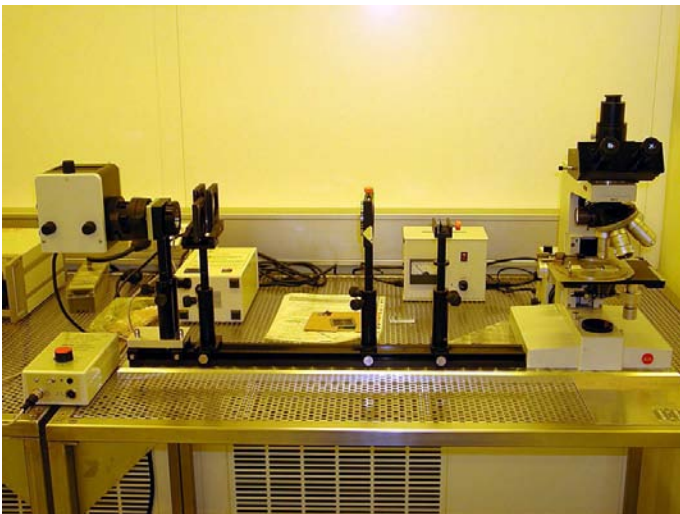


Figure 12: Top: Süss MJB 3 maskaligner for optical lithography. Bottom: Optical projection lithography based on an optical microscope.

Low and Ultra-low Temperature Facilities

The WMI operates several low and ultra-low temperature facilities that have been developed and fabricated in-house.

The lowest temperature is achieved by the nuclear demagnetization cryostat "Bayerische Millimühle 2". This ultra-low temperature facility consists of an in-house built dilution refrigerator and originally of two nuclear demagnetization stages. The first of those is based on a hyperfine enhanced van Vleck paramagnet PrNi_5 (0.9 mole), the second, which has been removed a few years ago, was based on purified copper (0.2 mole). The lowest temperature reached with this system was slightly below $30\text{ }\mu\text{K}$ in the copper nuclear spin system. At the moment, the first stage can be cooled to below $400\text{ }\mu\text{K}$ and, due to the large heat capacity of PrNi_5 , it stays below the mixing chamber temperature (5 mK) for nearly 3 weeks. In this cryostat three measuring sites are provided, two in a magnetic field compensated region and one in the center of an 8 T magnet. They are suitable for specific heat measurements, for capacitive torque- and SQUID magnetometry, as well as for transport measurements (electrical und thermal conductivity). The cryostat is also equipped with a pressure cell for liquid and solid ^3He , which at the moment is used for nuclear spin resonance measurements below 1 mK .

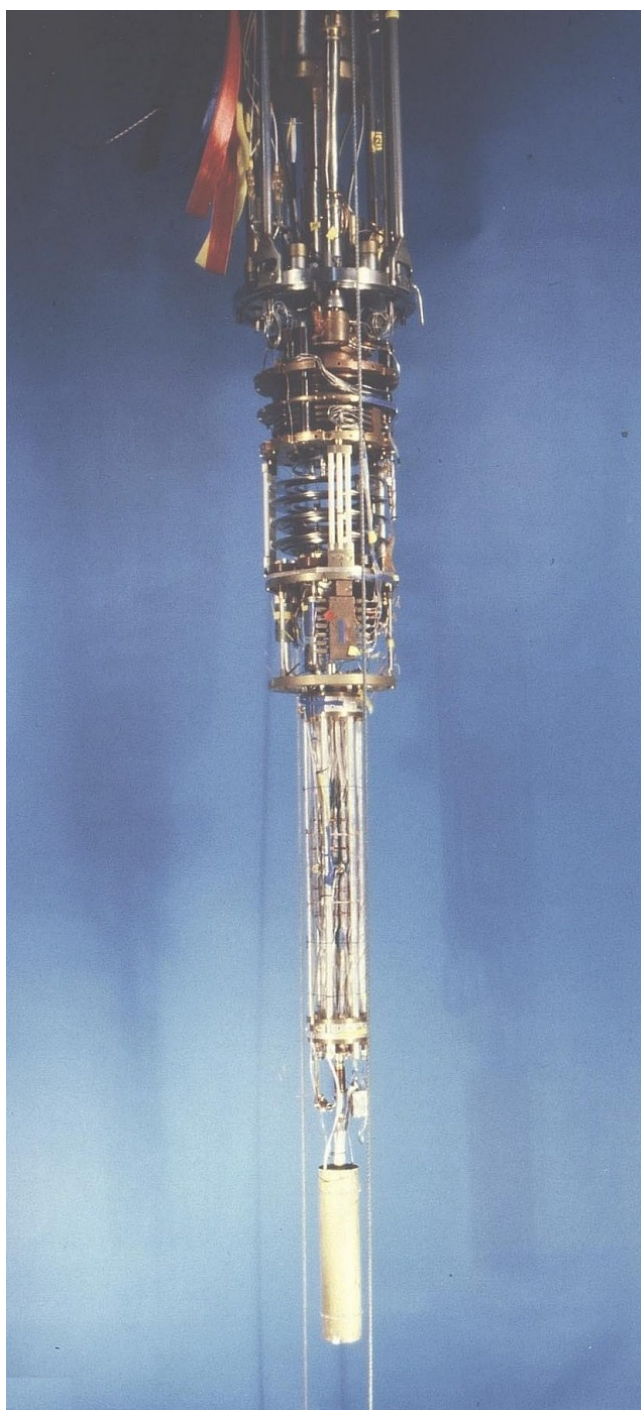


Figure 13: The dilution refrigerator and the nuclear demagnetization stage of the nuclear demagnetization cryostat "Bayerische Millimühle 2".

Some years ago, at the WMI, we have constructed the first dilution refrigerator with pulse tube pre-cooling for ultra-low temperature experiments. This type of refrigerator works without cryo-liquids, and thus is a lot more practical, more economical and more reliable than cryostats with liquid helium pre-cooling. These days, all major cryo-engineering firms are offering commercial versions of this milli-Kelvin cooler, and these so-called "dry" refrigerators outsell conventional refrigerators by a wide margin. The general construction concept of most manufacturers is unchanged from our original

prototype, where the refrigerator consists of three basic components. The first cooling stage is a commercial pulse tube cryocooler which reaches a base temperature of 2.5 K. The second stage is a Joule-Thomson stage, and the last stage is a dilution refrigeration stage, where the lowest temperature of the cryostat is about 0.01 K (Fig. 14).

In many low temperature applications high refrigeration capacities are required. Our design allows for a high circulation rate of ^3He which in the end determines the cooling power of a dilution refrigerator. Presently our "dry" fridge reaches a refrigeration capacity of $700\ \mu\text{W}$ at a temperature of the mixing chamber of 0.1 K, seven times the cooling power of the WMI nuclear demagnetization cryostat. Goals of our present work are a further increase of cooling power and a lower base temperature of the dry dilution refrigerator.



Figure 16: Two mixing chamber mounting plates with silver sponges. Those are needed to overcome the thermal resistance (Kapitza resistance) between the liquid ^3He and the mounting plate of the mixing chamber. To fabricate the mounting of the sponge (square pins embedded in the sponge) a spark erosion technique has been employed.



Figure 14: The "dry" dilution refrigerator of the WMI.



Figure 15: Low-temperature unit of a WMI dilution refrigerator ready to go into a cryostat.

A smaller version of our cryogen-free fridge has become commercially available at VeriCold Technologies, Ismaning. It has a refrigeration capacity of $250\ \mu\text{W}$ at a mixing chamber temperature of 0.1 K (Fig.15).



Figure 17: Dilution refrigerator insert with the Joule-Thompson stage, the heat exchanger and the mixing chamber.

The WMI also develops and fabricates dilution refrigerator inserts for temperatures down to about 20 mK. The inserts fit into all cryogenic systems (e.g. superconducting magnets) having a two inch bore. They allow fast sample change and rapid cool down cycles of less than five hours.

The dilution refrigerator inserts are engineered and fabricated in-house and are also provided to other low temperature laboratories for ultra low temperature experiments.

Low Temperature Scanning Tunneling Microscope with Ultra-High-Vacuum Characterization and Preparation Facilities

The low temperature scanning tunneling microscope allows investigation of low dimensional systems such as self-organized molecules, superconductors, magnetic and hetero-structure surfaces. The LT-STM is integrated into an ultra-high vacuum (UHV) chamber together with a variety of analytical as well as preparation tools. A newly added Quartz-Crystal-Microbalance allows quantitative controlling of evaporation processes. Monitoring is possible from island growth up to a film thickness of hundreds of atomic layers. The Hermann-group operates the LT-STM and the here listed preparation facilities in laboratory 028 at the WMI. B. A. Hermann is junior Principle Investigator of the excellence cluster Nanosystems Initiative Munich (NIM) and member of the Center for Nano Science (CeNS).

The Low Temperature Scanning Tunneling Microscope

The LT-STM (see figure 18 a) is designed for easy handling under UHV as well as low temperature conditions. We control the Omicron STM by an electronics of the RHK company (see figure 18 b).

Following, the technical features are listed:

- In-situ sample and tip exchange (manipulator see Figure 19 a).
- Vibration isolation ensured by a spring suspension system with eddy current damping and pneumatic damping legs.
- Variable temperatures from 5 K (pumped 2 K) up to room temperature (≈ 300 K).
- Fast system cool-down (5 K within ≈ 6 hours).
- Sample pre-cooling to 50 K on the manipulator stage.
- Fast sample cool-down (5 K within ≈ 2 hours).
- On-line optical access and on-line four terminal transport measurements.
- Up to 6 samples can be stored at low temperature (77 K).

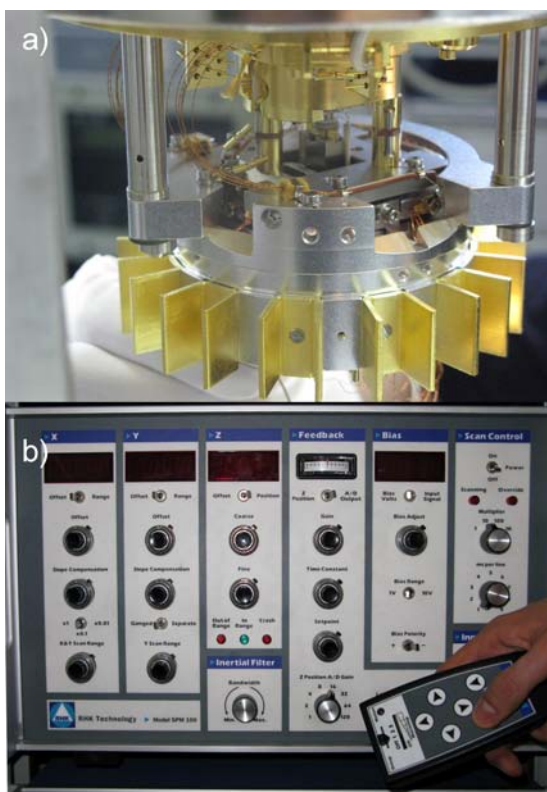


Figure 18: a) Inner view on the STM displaying part of the damping system, various cables and the scanning head (barely visible in the middle above the well). b) Photograph of our RHK scan electronic.

Preparation and Characterization Facilities

In addition to the LT-STM analysis chamber a second UHV chamber allows for sample preparation and characterization under UHV-conditions. Substrates can be prepared by an argon sputter gun and thermal annealing. A three crucible evaporator allows the deposition of molecules

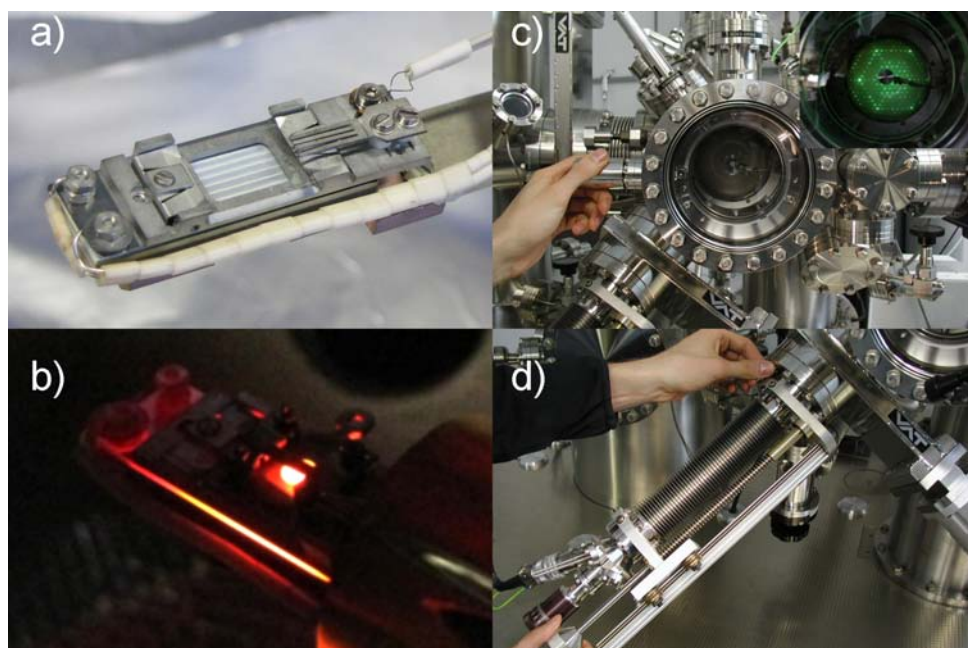


Figure 19: a) Close up on the manipulator for sample handling in the UHV chamber. b) Manipulator with Si-sample at 510°C under UHV conditions. The body of the manipulator is cooled to prevent damage. c) LEED spectrometer; inset LEED-diffraction image of the Si [111] 7×7 reconstruction. d) Photograph of the evaporator.

onto the surface; the deposition process is controlled by a quartz crystal microbalance. For sample characterization low-energy-electron-diffraction (LEED) and quadrupole mass spectrometry are available.

Argon Sputter Gun: Inside the preparation chamber clean single crystalline substrates are prepared by ion-sputtering and subsequent thermal annealing, which can be controlled by a three-grid low energy electron diffractometer (LEED) (see below) in a vacuum of 10^{-11} mbar.

Sample Heating/Cooling Stage: On the manipulator (see figure 19 a) samples can be prepared by direct current and indirect heating (see figure 19 b). Sample temperatures of up to 1073 K can be realized and the sample can be cooled to 50 K before transferring to the STM.

Low Energy Electron Diffraction (LEED): The surface ordering of (reconstructed) substrate/single crystal surfaces or molecular ad-layers can be analyzed by low energy electron diffraction (see figure 19 c).

Evaporator for Organic Material: A microprocessor controlled evaporator allows deposition of up to three different organic materials at the same time (see figure 19 d). Crucibles are re-filled without breaking the vacuum of the main chamber.

Quartz-Crystal-Microbalance: For controlling the evaporation process and quantitative measurements of the number of adsorbed layers on/coverage of the substrate during evaporation a quartz-crystal-microbalance was recently added. Growth rates of 0.01 nm/s corresponding to a frequency change of 0.03 Hz/s can be monitored.

Quadrupole Mass Spectrometer: Samples are additionally characterized by desorption spectroscopy with a quadrupole mass spectrometer. The desorbing molecules are ionized in a cross-beam ion source and accelerated in the quadrupole mass spectrometer, which either uses a Faraday cup or secondary electron multiplier (SEM) as detector with a mass resolution up to 2048 u.

Multiple additional vacuum ports allow further extensions of the Omicron STM in the future.

Tip etching facility (ex situ): The standard procedure for preparing STM tips - suitable for STM

measurements - is cutting a PtIr-wire with scissors. Other tip materials (e.g. Tungsten, Gold, Niobium,...) have to be etched in order to form the necessary tip radii. A newly constructed tip etching facility allows for more tip materials than PtIr opening up the possibility of usage of e.g. superconducting tips.

Magnetic Field Low Temperature Ultra-High-Vacuum (UHV) Scanning Tunneling Microscope (STM)

Built under the guidance of B. A. Hermann in the group of Prof. Dr. H.-J. Güntherodt in Basel, the system was transferred and put into operation in 2006; it complements the Omicron LT-STM operated at the WMI in Munich. The high stability of the instrument, the magnetic field as well as temperatures as low as 2.7 K allow the investigation of high temperature superconductors (HTSC) and organic superconductors. In a collaboration with A. Erb, R. Hackl as well as M. Kartsovnik and W. Biberacher, the group of B. A. Hermann currently investigates high-temperature superconductors and $ET_2Cu(NCS)_2$.

The STM is optimized for low temperature tunneling imaging and spectroscopy in high magnetic fields under UHV-conditions (see figure 20). A home-built electronics allows tunneling spectroscopy at points along lines, in grids and in a high density modus.



Figure 20: The current setup of the instrument: visible is the cryostat with microscope inside, as well as parts of the control electronics.

Technical Features of the STM:

- Imaging resolution:
0.01 nm in $x - y$ -direction and
0.005 nm in z -direction.
- Current-voltage spectroscopy ($I - V$)
(voltage resolution: 0.05 meV).
- Current-distance curves ($I - d$).
- Maximum scan size: $1 \mu\text{m} \times 1 \mu\text{m}$ at 4.2 K.
- Superconducting magnet up to 4 T with persistent switch.
- Vibration damping through spring suspension.
- Temperature range from room temperature down to liquid helium temperature at 4.2 K (pumped 2.7 K).
- Cryostat with LHe durability of one week (without thermal load).

Molecular Mechanics (MM)/Dynamics (MD) and Density Functional Theory (DFT) Based Simulation Package

Commercial simulation software available for materials science applications allows experimental groups to predict and understand the studied materials in a complementary way. Materials studio provides an easy to access interface to codes of the United Kingdom Car-Parinello Consortium for performing simulations to crosscheck experimental data on a day to day basis.

The Materials Studio is a modular simulation software consisting of Forcite Plus (molecular mechanics and molecular dynamics simulations), DMol³ (computational efficient DFT based calculations) and CASTEP (high accuracy DFT calculations).

Characteristics of Forcite Plus (MM and MD):

- single energy point properties,
- energy minimization of molecular structures,
- problem-optimized force fields (Universal, Dreiding, COMPASS etc.),
- non-periodic, 2D and 3D-periodic structures are supported,
- MD-simulation (see figure 21 a) in different thermodynamic ensembles (*NVT*, *NVE*, *NPH*, *NPT*) in a wide range of temperatures,
- quenching/annealing allowing search for global energy minimum,
- simulation of mechanical stress properties.

Characteristics of DMol³ (DFT):

- calculation of single energy point properties: band structure, density of states, electrostatic potential (see figure 21 b), orbitals etc.,
- problem-oriented usage via two local density approximation (LDA) functionals and eight generalized gradient approximation (GGA) functionals,
- MM-geometry optimization using the energies and forces calculated by DFT,
- dynamical simulation of electronic sample properties in two thermodynamic ensembles (*NVT*, *NVE*),
- continuous solvation model for as much as 15 different solvents,

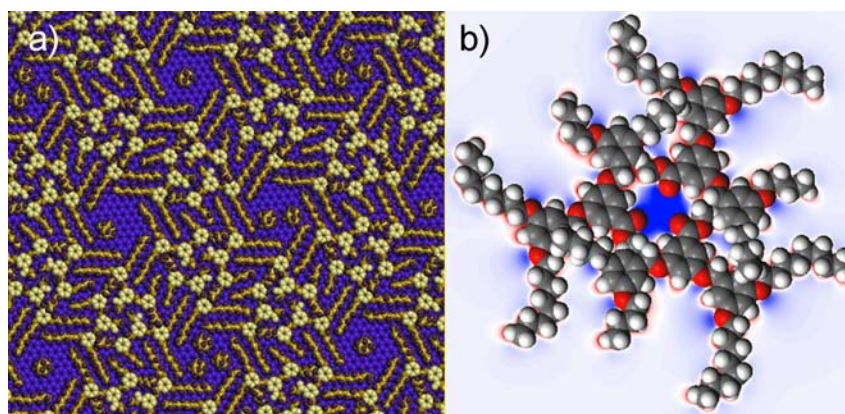


Figure 21: a) Molecular Dynamics simulation of a Fréchet-Dendron monolayer (Forcite Plus), b) DFT calculated electrostatic potential of a trimeric molecular ordering (DMol³)

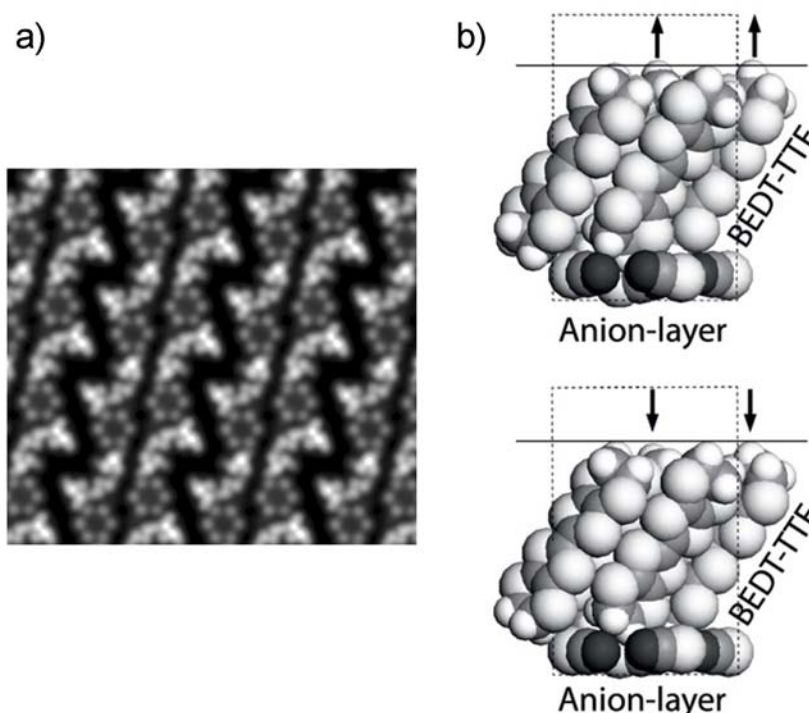


Figure 22: a) With CASTEP simulated STM image: integrated local density of states (LDOS) of Fréchet dendrons co-adsorbed with corone molecules; b) Quasi-Newton scheme relaxation of an organic superconductor surface.

- search for the inversion point (transition state) in the energy landscape of a chemical reaction (energy barrier, reaction pathway).

Characteristics of CASTEP (DFT):

- high precision calculation of single energy point properties: band structure, local density of states, orbitals, NMR, optical properties, phonons, stress etc.,
- one LDA and four GGA functionals as well as five nonlocal-exchange-correlation functionals (better description of semiconductors and insulators),
- MM-geometry optimization using the energies and forces calculated by DFT,
- simulation of various dynamic sample properties (band structure, s. above) in four different thermodynamic ensembles or under elastic stress,
- simulation of constant height STM-images: integrated local density of states at various bias voltage (see figure 22 a),
- search for transition states (e.g. in chemical reactions),
- Quasi-Newton scheme (BGFS approach) structure relaxation using discrete minimization steps based on DFT calculations (see figure 22 b).

Cantilever Sensor System with Temperature Control and Cell Handling Environment

With their small size, fast response time, and direct signal transduction without the need for labeling, cantilever sensors hold an enormous potential for applications in the field of (bio)chemical recognition. Advantages of this technology in addition to their high sensitivity

are parallel detection of multiple analytes (multiplexed assays), flexibility with respect to the choice of systems to be investigated, real-time analysis and on-line reference channels.

With a core competence in molecular self-organization and scanning probe microscopy, the Hermann group pursues application of this knowledge towards enabling and controlling a Concentris[®] cantilever array (see figure 23 a) setup for the detection of (bio-)chemical key-lock interactions. (Bio)sensing devices are developed based on arrays of functionalized cantilevers (see figure 23 b-d) that act as extremely sensitive and highly specific receptors for chemical or biological substances under accurate temperature control.

In the following, the technical features are listed:

- Temperature control from 290 K to 340 K.
- Preheating stage allowing temperature stability better than 0.05 K.
- Vibration damping.
- Force (F) or surface stress (σ) resolution in static mode: $F = 10^{-9}$ N; $\sigma = 10^{-4}$ N/m
- Frequency resolution 0.1 ppm in the dynamic mode (10 mHz@100 kHz). Dynamic range from 10 kHz to 2 MHz.
- Example of mass load detection in the dynamic mode in vacuum: 0.025 fg/mm²/Hz corresponding to $m = 10^{-18}$ g (from B. Illic et al., J. Appl. Phys., 95, 7 (2004)).
- Simultaneous measurements of static mode signals and dynamic mode signals in liquids (0.1 to 10 Hz sampling rate).
- Optical beam deflection system; Resolution of differential deflection < 2nm (best case) or < 5nm (average case).
- Arrays of 8 parallel, stabilized single-mode vertical-cavity surface-emitting lasers (VCSEL's, wavelength 850 nm) for optical read-out.
- Bio-compatible measurement cell with a volume of only 5 μ l.
- Capable of measuring (bio-) chemical reaction dynamics in real-time.
- Integrated liquid handling system: liquid flow rates ranging from 0.4 μ l/sec to 50.0 μ l/sec.

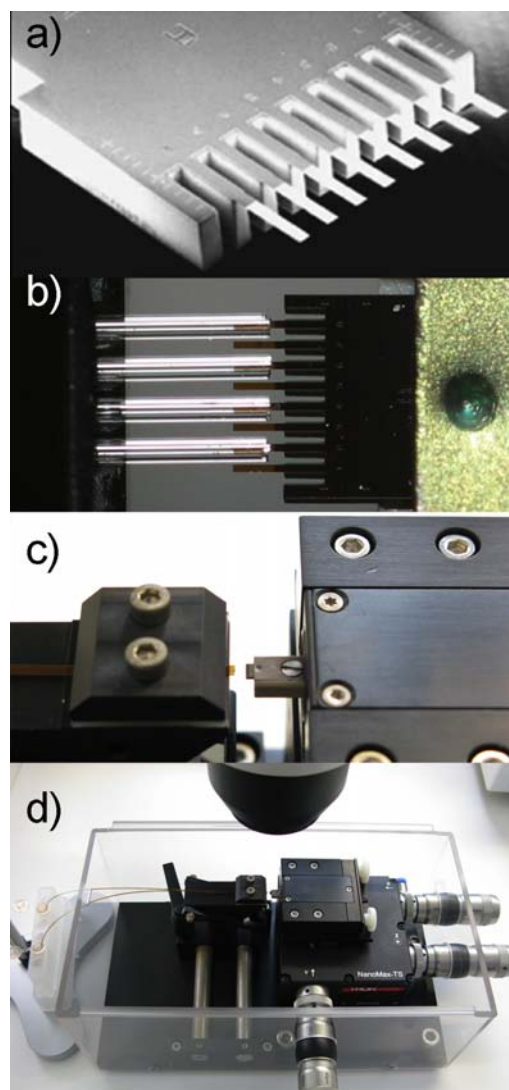


Figure 23: The cantilever and handling system in detail: a) cantilever array, b) array inside functionalization capillaries, c) handling cartridge inside functionalization unit d) mechanics of the functionalization unit.

Cell Handling Equipment

The work with cells requires laboratory conditions that are optimized for cell growth and handling. The cell handling/cantilever array measurements proceed as follows:

- a) cleaning of the glassware and cell culture medium in an autoclave,
- b) culturing of the cells in the nutrient inside an incubation-shaker,
- c) taking up of the cells in the buffer medium in a clean environment established by a laminar flow bio work bench (see figure 24),
- d) attaching bioreceptors on the cantilever's eight parallel sensors employing our functionalization unit also placed the lamina flow box,
- e) mounting of the cantilever array in the cantilever sensor system under constant buffer flow,
- f) injecting the cell containing analyte into the measurement chamber,
- g) repeated measuring of the sensor response by beam deflection, recovery between measurements,
- h) vacuum drying and freezing of the cantilever array for later experiments and parts of the cell cultures for later re-cultivation.

The laminar flow (bio) work bench and the vacuum concentrator facility also provide the necessary clean working environment for detecting antibodies. Hence, to maintain optimal clean working conditions the Cantisens sensor platform as well as the functionalization unit are also placed within the laminar flow box. The clean environment (bio) work bench set-up in our laboratory includes the following components:

- Laminar flow box of (class 5, bench size 1800 x 900 x 1200 mm, clear back wall and side windows).
- Incubation-shaker (10 mm orbit, max. loading 2.5 kg, temperature regulation between 25°C – 42°C with a stability of 0.1°C, speed range 50 – 250 rpm).
- Vacuum concentrator (for 1.5/ 2 ml Eppendorf vials, vacuum < 20 mbar employing a PTFE-membrane pump).

This research on protein-carbohydrate, bacterial, cell and gene interactions is integrated in the ERA Chemistry project and the Excellence Cluster "Nanosystems Initiative" (NIM) Munich.



Figure 24: Clean environment (bio) work bench: Cantilever setup and cell-handling equipment inside the laminar flow box.

Publications

1. S. Geprägs, F.D. Czeschka, M. Opel, S.T.B. Goennenwein, W. Yu, W. Mader, and R. Gross,
Epitaxial Growth and Magnetic Properties of $\text{Sr}_2\text{CrReO}_6$ Thin Films
J. Magn. Magn. Mat. **321**, 2001–2004 (2009).
2. D. Venkateshvaran, M. Althammer, A. Nielsen, S. Geprägs, M.S. Ramachandra Rao, S. T. B. Goennenwein, M. Opel, and R. Gross,
Epitaxial $\text{Zn}_x\text{Fe}_{3-x}\text{O}_4$ Thin Films: A Spintronic Material with Tunable Electrical and Magnetic Properties
Phys. Rev. B **79**, 134405 (2009).
3. M. Weiler, A. Brandlmaier, S. Geprägs, M. Althammer, M. Opel, C. Bihler, H. Huebl, M. S. Brandt, R. Gross, S. T. B. Goennenwein
Voltage Controlled Inversion of Magnetic Anisotropy in a Ferromagnetic Thin Film at Room Temperature
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4. T. Niemczyk, F. Deppe, M. Mariani, E.P. Menzel, E. Hoffmann, G. Wild, L. Eggenstein, A. Marx, R. Gross
Fabrication Technology of and Symmetry Breaking in Superconducting Quantum Circuits
Supercond. Sci. Techn. **22**, 034009 (2009).
5. C. Rohr, J.M. Büttner, F.A. Palitschka, N.D. Kushch, M.V. Kartsovnik, W. Biberacher, R. Gross, B.A. Hermann
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6. T. Helm, M.V. Kartsovnik, M. Bartkowiak, N. Bittner, M. Lambacher, A. Erb, J. Wosnitzer, R. Gross
Evolution of the Fermi Surface of the Electron-Doped High-Temperature Superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ Revealed by Shubnikov-de Haas Oscillations
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7. R. Gross, D. Einzel
Von Walther Meißner zum Quanten-Bit
Akademie Aktuell **2**, 47–49 (2009).
8. F.D. Czeschka, S. Geprägs, M. Opel, S.T.B. Goennenwein, R. Gross
Giant magnetic anisotropy changes in $\text{Sr}_2\text{CrReO}_6$ thin films on BaTiO_3
Appl. Phys. Lett. **95**, 062508 (2009).
9. M. V. Kartsovnik, P. D. Grigoriev, W. Biberacher, and N. D. Kushch
Magnetic field induced coherence-incoherence crossover in the interlayer conductivity of a layered organic metal
Phys. Rev. B (Rapid Com.) **79**, 165120 (2009).
10. I. A. Nekrasov, N. S. Pavlov, E. Z. Kuchinskii, M. V. Sadovskii, Z. V. Pchelkina, V. B. Zabolotnyy, J. Geck, B. Büchner, S. V. Borisenko, D. S. Inosov, A. A. Kordyuk, M. Lambacher, and A. Erb
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Phys. Rev. B (Rapid Com.) **80**, 140510 (2009).
11. B. Muschler, W. Prestel, R. Hackl, T.P. Devereaux, J.G. Analytis, Jiun-Haw Chu, I.R. Fisher,
Band- and momentum-dependent electron dynamics in superconducting $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)\text{As}_2$ as seen via electronic Raman scattering
Phys. Rev. B **80**, 180510 (2009).
12. Kalobaran Maiti, Jörg Fink, Sanne de Jong, Mihaela Gorgoi, Chengtian Lin, Markus Raichle, Vladimir Hinkov, Michael Lambacher, Andreas Erb, and Mark S. Golden
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13. M.V. Kartsovnik, D. Andres, W. Biberacher, H. Müller
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14. S.I. Pesotskii, R.B. Lyubovskii, M.V. Kartsovnik, W. Biberacher, N.D. Kushch, A. Kobayashi, B. Zhou
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15. Ferdinand Helmer, Matteo Mariantoni, Austin G. Fowler, Jan von Delft, Enrique Solano, and Florian Marquardt
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16. M. Glunk, J. Daeubler, L. Dreher, S. Schwaiger, W. Schoch, R. Sauer, W. Limmer, A. Brandlmaier, S. T. B. Goennenwein, C. Bihler and M. S. Brandt
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Phys. Rev. B **79**, 195206 (2009).
17. Ferdinand Helmer, Matteo Mariantoni, Enrique Solano, and Florian Marquardt
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Phys. Rev. A **79**, 052115 (2009).
18. C. Bihler, W. Schoch, W. Limmer, S. T. B. Goennenwein, and M. S. Brandt
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19. L. Klam, D. Einzel, D. Manske
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Phys. Rev. Lett. **102**, 027004 (2009).
20. J.S. White, V. Hinkov, R.W. Heslop, R.J. Lycett, E.M. Forgan, C. Bowell, S. Straessle, A.B. Abrahamson, M. Laver, C.D. Dewhurst, J. Kohlbrecher, J.L. Gavilano, J. Mesot, B. Keimer, A. Erb
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Phys. Rev. Lett. **102**, 097001 (2009).
21. S.P. Crane, C. Bihler, M.S. Brandt, S.T.B. Gönnerwein, M. Gajek, R. Ramesh
Tuning magnetic properties of magnetoelectric BiFeO $_3$ -NiFe $_2$ O $_4$
Journal of Magnetism and Magnetic Materials **321**, L5–L9 (2009).
22. K. Uhlig
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23. W.H. Lim, H. Hübl, L.W. Willems van Beveren, S. Rubanov, P.G. Spizzirri, S.J. Angus, R.G. Clark, A.S. Dzurak
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Appl. Phys. Lett. **94**, 173502 (2009).
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Phys. Rev. B **80**, 081307 (2009).
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Review of Scientific Instruments **80**, 114705 (2009).
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27. E. Schuberth, M. Tippmann, M. Kath, C. Krellner, C. Geibel, T. Westerkamp, C. Klingner, F. Steglich
Magnetization Measurements on YbRh_2Si_2 at Very Low Temperatures
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28. M. Grilli, S. Caprara, C. Di Castro, T. Enss, R. Hackl, B. Muschler, W. Prestel
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Physica B **404**, 3070–3074 (2009).
29. R. Huber, P. Klemm, S. Neusser, B. Botters, A. Wittmann, M. Weiler, S.T.B. Gönnenwein, C. Heyn, M. Schneider, P. Böni, D. Grundler
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30. W.H. Lim, F.A. Zwanenburg, H. Huebl, M. Möttönen, K.W. Chan, A. Morello, A.S. Dzurak
Observation of the single-electron regime in a highly tunable silicon quantum
Appl. Phys. Lett., accepted for publication (2009).
31. A. Ney, M. Opel, T.C. Kaspar, V. Ney, S. Ye, K. Ollefs, T. Kammermeier, S. Bauer, K.-W. Nielsen, S.T.B. Gönnenwein, M.H. Engelhard, S. Zhou, K. Potzger, J. Simon, W. Mader, S.M. Heald, J.C. Cezar, F. Wilhelm, A. Rogalev, R. Gross, S.A. Chambers
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32. C. Pfleiderer, T. Adams, A. Bauer, W. Biberacher, B. Binz, F. Birkelbach, P. Böni, C. Franz, R. Georgii, M. Janoschek, F. Jonietz, R. Ritz, S. Mühlbauer, W. Münzer, A. Neubauer, B. Pedersen, A. Rosch,
Skymion Lattices in Metallic and Superconducting B20 Transition Metal Compounds
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33. B.G.U. Englert, G. Mangano, M. Mariani, R. Gross, J. Siewert, and E. Solano
Mesoscopic Shelving Readout of Superconducting Qubits in Circuit QED
Phys. Rev. B, submitted for publication (2009); arXiv:0904.1769.
34. Georg M. Reuther, David Zueco, Frank Deppe, Elisabeth Hoffmann, Edwin P. Menzel, Thomas Weißl, Matteo Mariani, Sigmund Kohler, Achim Marx, Enrique Solano, Rudolf Gross, Peter Hänggi
Two-resonator Circuit QED: Dissipative Theory
Phys. Rev. B, submitted for publication (2009); arXiv:0911.2657.
35. M. Wagenknecht, M. Rahlenbeck, D. Koelle, R. Kleiner, A. Tsukada, S.T.B. Gönnenwein, R. Gross
Grain Boundary Tunnel Spectroscopy of the Electron Doped Cuprate Superconductor $\text{La}_{2-x}\text{Ce}_x\text{CuO}_4$ in Low and High Magnetic Fields
Phys. Rev. B, submitted for publication (2009).
36. K. Uhlig,
Improved Design of the Intermediate Stage of a Dry Dilution Refrigerator
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37. S. Thirupathaiah, S. de Jong, R. Ovsyannikov, H.A. Dürr, A. Varykhalov, R. Follath, Y. Huang, R. Huisman, M.S. Golden, Yu-Zhong Zhang, H.O. Jeschke, R. Valenti, A. Erb, A. Gloskovskii, J. Fink,
Orbital character variation of the Fermi surface and doping dependent changes of the dimensionality in $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ from angle-resolved photoemission spectroscopy
Phys. Rev. Lett., submitted for publication (2009).
38. M. Kemmler, M. Weides, M. Weiler, M. Opel, S.T.B. Gönnenwein, A.S. Vasenko, A.A. Golubov, H. Kohlstedt, D. Koelle, R. Kleiner, E. Goldobin,
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Phys. Rev. B, submitted for publication (2009).
39. C. Rohr, M. Balbás Gamba, K. Gruber, E.C. Constable, E. Frey, T. Franosch, B.A. Hermann,

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40. B.A. Hermann, C. Rohr, M. Balbás Gamba, K. Gruber, A. Malecki, E.C. Constable, E. Frey, T. Franosch,
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Phys. Rev. B, submitted for publication (2009).
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Detecting Carbohydrate-Protein Recognition in Nanomolar Sensitivity with Cantilever Array Sensors
Proc. Natl. Acad. Sci., submitted for publication (2009).
42. M. Lavagnini, H.-M. Eiter, L. Tassini, B. Muschler, R. Hackl, R. Monnier, J.-H. Chu, I.R. Fischer, L. Degiorgi,
Raman scattering evidence for a cascade-like evolution of the charge-density-wave collective amplitude mode
Phys. Rev. Lett., submitted for publication (2009).
43. N. Munnikes, B. Muschler, F. Venturini, L. Tassini, W. Prestel, Shimpei Ono, Yoichi Ando, A. Damascelli, H. Eisaki, M. Greven, A. Erb, R. Hackl,
Pair breaking versus symmetry breaking: Origin of the Raman modes in superconducting cuprates
Phys. Rev. B, submitted for publication (2009).

Theses, Appointments, Honors and Awards, Membership in Advisory Boards, etc.

Completed and ongoing Ph.D. Theses

1. **Superconducting Flux Quantum Circuits: Characterization, Quantum Coherence, and Controlled Symmetry Breaking**
Frank Deppe, TU München, April 2009.
2. **Magnetit – ein Material für die Spinelektronik**
Andrea Nielsen, TU München, Juni 2009.
3. **Kernspindynamik in festem ^3He bei ultratiefen Temperaturen**
Matthias Kath, TU München, November 2009.
4. **New Trends in Superconducting Circuit Quantum Electrodynamics: Two Amplifiers, Two Resonators, and Two Photons**
Matteo Mariani, TU München, Dezember 2009.
5. **Effizientes Design von Planar-Transformatoren**
Thomas Florian Goßner, Dezember 2009.
6. **Supraleitende Quantenbits mit Supraleiter-Ferromagnet-Supraleiter Josephson-Kontakten**
Georg Wild, TU München, seit September 2004.
7. **Spin-Engineering in funktionalen Schichtsystemen aus Übergangsmetalloxiden**
Stephan Geprägs, TU München, seit Oktober 2004.
8. **Untersuchung der Wechselwirkungspotenziale in Kupratsupraleitern durch quantitativen Vergleich spektroskopischer Resultate**
Wolfgang Prestel, TU München, seit November 2004.
9. **Kohärente Dynamik und Dekohärenz in supraleitenden Quantenbits**
Edwin Menzel, TU München, seit Januar 2006.
10. **Quantenelektrodynamik mit supraleitenden Schaltkreisen**
Thomas Niemczyk, TU München, seit Juli 2006.
11. **Multiferroisches Verhalten und steuerbarer Magnetismus in oxidischen Heterostrukturen**
Andreas Brandlmaier, TU München, seit Dezember 2006.
12. **Tieftemperatur-Rastersondenmikroskopie an Molekülsystemen und Nanotubes**
Carsten Rohr, LMU München, seit Januar 2007.
13. **Hybride Nanostrukturen auf der Basis von Materialsystemen mit elektronischen Korrelationen**
Franz Czeschka, TU München, seit Juli 2007.
14. **(Bio) Sensorik mit Cantileverarrays und Oberflächenkontrolle mittels Rastersondentechniken**
Kathrin Gruber, LMU München, seit November 2007.
15. **Korrelierte Systeme untersucht mit Tieftemperatur-Rastersondenmikroskopie**
Johannes Büttner, LMU München, seit Januar 2008.
16. **Magnetotransporteigenschaften von dünnen ferromagnetischen Schichten und Heterostrukturen**
Mathias Weiler, TU München, seit Februar 2008.
17. **Untersuchung von Kupraten nahe des Einsatzpunktes der Supraleitung**
Bernhard Muschler, seit Februar 2008.

18. **Multifunktionale magnetische Heterostrukturen**
Matthias Althammer, TU München, seit April 2008.
19. **Herstellung und Charakterisierung von supraleitenden Schaltkreisen zur Realisierung von gekoppelten supraleitenden Quantenbauelementen**
Elisabeth Hoffmann, TU München, seit April 2008.
20. **Quantenexperimente mit elektromechanischen Systemen**
Fredrik Hocke, TU München, seit Mai 2008.
21. **Spininjektion und Spintransport in ZnO-basierten Schichtsystemen**
Deepak Venkateshvaran, TU München, seit Oktober 2008.
22. **Wechselwirkung zwischen Spin-, Gitter- und Ladungsfreiheitsgraden in korrelierten Metallen ohne Inversionszentrum**
Hans-Martin Eiter, TU München, seit Oktober 2008.

The following PhD students of the Walther-Meißner-Institute have finished their theses in 2009:



Frank Deppe



Andrea Nielsen



Matthias Kath



Matteo Mariani

Completed and ongoing Diploma, Bachelor, Master Theses

1. **Transport Measurements in 214 High Temperature Superconductors**
Toni Helm, Januar 2009.
2. **Tribologische Charakterisierung diamantartiger amorpher Kohlenstoffe**
Andreas Oancea, TU München, Januar 2009
3. **Non-linear Spin-dependent Nanodevices Based on Magnetic Double Tunnel Junctions**
Arndt von Bieren, TU München, Januar 2009.
4. **Synthesis and Characterization of Iron Arsenic (FeAs) Based Superconductors**
Monika Bahurupi, TU München, März 2009.
5. **Optimierung und Charakterisierung von supraleitenden Quantenschaltkreisen auf Basis von Fluss-Quantenbits**
Lars Eggenstein, TU München, Juli 2009.
6. **Herstellung, Charakterisierung und Untersuchung hochgeordneter Y-123 Einkristalle**
Timo Buttler, TU München, Juni 2009.
7. **Surface Acoustic Waves at Ferromagnetic Piezoelectric Interfaces**
Hajo Söde, TU München, Juli 2009.
8. **Magneto-optical Investigation of Multiferroic Hybrid Structures**
Matthias Brasse, Oktober 2009.
9. **Winkelaufgelöster Magnetotransport an ferromagnetischen Filmen**
Michael Albert Wagner, Oktober 2009.
10. **Nonlocal Phenomena in Metallic Nanostructures**
Daniel Rüffer, November 2009.
11. **Supraleitende Quantenschalter**
Thomas Weißl, Dezember 2009.
12. **Cross-Correlation Measurements of Squeezed Microwave States Using a Josephson Parametric Amplifier**
Alexander Baust, seit Juli 2009.
13. **Hochfrequente mechanische Verspannung und Magnetotransporteigenschaften von ferromagnetischen Dünnschichtstrukturen**
Christian Heeg, seit Mai 2009.
14. **Surface Plasmons at Magnetic Interfaces**
Themistoklis Sidiropoulos, seit September 2009.
15. **Herstellung und Charakterisierung von magnetischen Dünnschichten mit hoher Spinpolarisation**
Alexander Krupp, seit November 2009.
16. **Untersuchung der elektronischen Eigenschaften von FeAs-Verbindungen bei hohen Drücken**
Reinhard Roßner, seit November 2009.

Appointments, Membership in Advisory Boards, etc.

1. **Rudolf Hackl** is member of the Advisory Board of the Conference “Low Energy Electron Dynamics LEES 2010”
2. **Rudolf Gross** is member of the Scientific Advisory Board of the Leibniz Institute for Solid-State and Materials Research, Dresden.
3. **Rudolf Gross** is member of the Kuratorium of the Physik Journal of the German Physical Society.
4. **Rudolf Gross** is spokesman of the section *Low Temperature Physics* of the Condensed Matter Division of the German Physical Society.
5. **Sebastian Gönnerwein** is associate member of the Cluster of Excellence *Nanosystems Initiative Munich (NIM)*.
6. **Werner Biberacher** is member of the Selection Panel EuroMagNet II of the Joint European High Magnetic Field Laboratories.
7. **Dietrich Einzel** is one of the four spokesmen of the scientific staff of the Bavarian Academy of Sciences and Humanities.
8. **Rudolf Gross** is member of the International Advisory Board of the Institute for Nanoscale Physics and Chemistry (INPAC), which has been established by the Katholieke Universiteit Leuven in 2006 in the framework of its Excellence Programme.
9. **Rudolf Gross** is member of the Board of Editors of the European Physical Journal B.

Research Projects and Cooperations

A large number of our research projects are benefiting from the collaboration with external groups in joint research projects, as well as from individual collaborations, exchange programs and visitors. Most collaborations are based on joint projects, which are funded by different research organizations (see list below). A considerable number of collaborations also exists with universities, other research institutions and industry without direct financial support.

Funded Projects

German Research Foundation: Excellence Initiative

Cluster of Excellence "Nanosystems Initiative Munich"

1. Project Area A: *Single Electron and Spin Systems*
R. Gross, S.T.B. Gönnerwein
2. Project Area C: *Quantum Information Nanosystems*
R. Gross, A. Marx
3. Project Area F: *Nanoanalytics and Enabling Techniques*
B.A. Hermann

German Research Foundation: Collaborative Research Centers

Collaborative Research Center 631: "Solid-State Quantum Information Processing: Physical Concepts and Materials Aspects"

1. Project A3: *Superconducting Quantum Circuits as Basic Elements for Quantum Information Processing*
R. Gross, A. Marx
2. Project A8: *Cavity Quantum Electrodynamics with Superconducting Devices*
A. Marx, R. Gross
3. Project S: *Coordination of the Collaborative Research Center*
R. Gross

Transregional Collaborative Research Center TRR 80: "From Electronic Correlations to Functionality"

1. Project A2: *Spatially und Momentum Resolved Raman Studies of Correlated Systems*
R. Hackl

German Research Foundation: Research Units

Research Unit 538: “Doping Dependence of Phase Transitions and Ordering Phenomena in Cuprate Superconductors”

1. Project: *Single Crystal Growth of p- and n-doped Cuprate Superconductors*
A. Erb, R. Gross
2. Project: *Raman Studies of Competing Ordering Phenomena in Cuprates*
R. Hackl, R. Gross
3. Project: *Coordination of the Research Unit*
R. Hackl

German Research Foundation: Priority Programs

1. Project: *Novel functional layer structures based on artificial heteroepitaxial multilayers of transition metal oxides*
within the DFG Priority Program 1157 “Integrated Electroceramic Functional Structures”
R. Gross (Az. GR 1132/13-1, GR 1132/13-2 and 1132/13-3)
2. Project: *Spin injection, spin transport and controllable ferromagnetism in transition metal doped ZnO*
within the DFG Priority Program 1285 “Halbleiter-Spinelektronik”
R. Gross, S.B.T. Gönnerwein, M. Opel (Az. GR 1132/14-1, GR 1132/14-2)
3. Project: *Raman study of electron dynamics and phase transitions in iron-pnictide compounds*
within the DFG Priority Program 1458 “High-Temperature Superconductivity in Iron-Pnictides”
R. Hackl, R. Gross, B. Büchner, D. Johrendt, C. Honerkamp (Az. HA 2071/7-1)

German Research Foundation: Research Projects

1. Project: *Interaction between spin, lattice, and charge in non-centrosymmetric correlated metals*
R. Hackl, R. Gross (Az. HA 2071/5-1)
2. Project: *Effect of pressure, magnetic fields, and crystal quality on the electronic ground states of low-dimensional organic conductors*
W. Biberacher (Az. 436 RUS 113/926/0-1)
3. Project: *Local Magnetotransport Properties of Thin Ferromagnetic Layers and Heterostructures*
S.T.B. Gönnerwein (Az. GO 944/3-1)

European Union

1. ERA-Chemistry-network: "Hierarchically organized chemical structures: from molecules to hybrid materials", project: *Probing Hierarchical Self-Assemblies Relevant for Drug and Vaccine Design by Employing STM*
B.A. Hermann (project number ERA HE 5162/1-1)
2. Marie Curie Network for Initial Training (ITN): "Cavity-confined Luminophores for Advanced Photonic Materials: A Training Action for Young Researchers" (FINELUMEN)
R. Hackl, Grant Agreement Number PITN-GA-2008-215399
partners: several European Universities and research facilities.
3. COST Action CM0601: "Electron Controlled Chemical Lithography (ECCL)", project in Working Group 3: *Chemical control by scanning tunneling microscopy*
B.A. Hermann

Alexander von Humboldt Foundation

1. Institutspartnerschaft "Kamaras-Hackl"
R. Hackl (Förderkennzeichen 3-Fokoop-DEU/1009755)

Ministerio de Educacion y Ciencia, Spanien

1. Intercalación de minerales de la arcilla por medio de tratamiento con ultrasonidos y reacciones de transferencia de electrones. Producción de arcillas funcionalizadas con estructuras complejas jerarquizadas en el espacio interlaminar.
J.L. Perez-Rodriguez, A. Lerf (Reference No. : MAT2005-04838)

International Doctorate Program NanoBioTechnology – IDK-NBT

1. project: *STM on magnetic layers and self-organized magnetic molecules*
B.A. Hermann, coordination by C. Bräuchle and J. Rädler (IDK-NBT 1506-42501-1)

Bavaria California Technology Center (BaCaTeC)

1. Collaboration project on *Materials with coupled order parameter under extreme conditions*
R. Hackl,
partners: Profs. T.P. Devereaux, I. Fischer, W.L. Mao

Conferences and Workshops

The Walther-Meißner-Institute has organized/co-organized the following conferences and workshops in 2009:

1. **International Workshop and School on “Solid State Based Quantum Information (QIP 2009)”**
June 28 - July 3, 2009, Herrsching, Germany.



The workshop was jointly organized by the Munich Research Centers (Collaborative Research Center 631 and the Cluster of Excellence NIM) and the quantum information groups at the TU Delft, the University of Basel and the ETH Zürich. The meeting was bringing together more than 150 scientists, working on solid state quantum information systems both in theory and experiment.

2. **Course 3 on “Applied Physics and Electronics” of the Ferienakademie 2009**
September 20 – October 02, 2009, Sarntal, Italy.



The course was held together with Prof. Klaus Mecke from the University of Erlangen/Nuremberg within the Ferienakademie. The Ferienakademie is jointly organized by the Technische Universität München, the University of Erlangen/Nuremberg, and the University of Stuttgart and takes place in the Italian Alps.

Collaborations

Other collaborations without direct project funding involve:

- Stanford University, Stanford, USA (Prof. T.P. Devereaux, M. Greven, Z.-X. Shen, I. Fisher)
- Institute for Quantum Computing, University of Waterloo, Waterloo, ON, Canada (Prof. Dr. F.K. Wilhelm)
- Departamento de Química Física, Universidad del País Vasco - Euskal Herriko Unibertsitatea, Bilbao, Spain (Prof. E. Solano)
- NTT Basic Research Laboratories, Japan (Dr. K. Semba)
- Nano Electronics Research Laboratories, NEC Corporation, Japan (Dr. Y. Nakamura, Dr. J.S. Tsai, Dr. T. Yamamoto)
- Instituto de Ciencia de Materiales de Sevilla, Spain (Prof. J. Poyato, Prof. J.L. Perez-Rodriguez)
- Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences, Budapest, Hungary (Prof. K. Kamaras and Prof. I. Tüttö)
- University of Rome "La Sapienza", Rome, Italy (Prof. S. Caprara, Prof. C. Di Castro and Prof. M. Grilli)
- Hungarian Academy of Sciences, Budapest University of Technology and Economics, Budapest, Hungary (Dr. A. Virosztek, Prof. A. Zawadowski, Prof. A. Janossy)
- Central Research Institute of the Electric Power Industry, Tokyo, Japan (Dr. S. Ono and Dr. Y. Ando)
- University of Fribourg (Prof. C. Bernhard)
- University of Basel, Institute of Inorganic Chemistry, Switzerland (Prof. E. Constable, Prof. C. Housecroft)
- University of Basel, Institute of Physics, Switzerland (Prof. H.-J. Güntherodt)
- European Synchrotron Radiation Facility (ESRF), Grenoble (Dr. H. Müller, Dr. J. Criginski Cezar, Dr. D. Mannix)
- LEPES, CNRS, Grenoble (Dr. J. Dumas and Prof. C. Schlenker)
- Materials Science Research Centre, IIT Madras, India (Prof. M.S. Ramachandra Rao)
- High Magnetic Field Laboratory, Toulouse (C. Proust, D. Vignolles)
- Kungliga Tekniska Högskolan (KTH) Stockholm, Sweden (Dr. G. Vaitheeswaran, Dr. V. Kanchana)
- ETH-Zurich, Switzerland (Prof. P. Seeberger)
- Chalmers University of Technology Gothenburg, Sweden (Prof. P. Delsing)
- Universidad del País Vasco, San Sebastian, Spain (Prof. A. Rubio)
- MINT Center, University of Alabama (Prof. A. Gupta)
- Materials Physics Laboratory, Helsinki University of Technology, Finland (Dr. Tero Heikkilä)
- Department of Condensed Matter Physics, The Weizmann Institute of Science, Israel (Dr. Moshe Schechter)
- Kavli Institute of NanoScience, Delft University of Technology, Delft, The Netherlands (Prof. T.M. Klapwijk)
- Institute for Experimental Physics, Slovakian Academy of Sciences, Kosice (Prof. K. Flachbart)

- High-Magnetic-Field Laboratory, Grenoble, France (Dr. I. Sheikin)
- B. Verkin Institute for Low Temperature Research and Engineering, Kharkov, Ukraine (Prof. V.G. Peschansky)
- Landau Institute for Theoretical Physics, Chernogolovka, Russia (Dr. P. Grigoriev)
- Russian Academy of Sciences, Chernogolovka, Russia (N. Kushch, A. Palnichenko)
- High Magnetic Field Laboratory, Dresden (M. Bartkowiak, J. Wosnitzer)
- University of Bonn, Germany (Prof. W. Mader)
- IFW Dresden, Germany (Prof. B. Büchner, Prof. J. Fink, Dr. S.V. Borisenko, Dr. M. Knupfer)
- Max-Planck-Institut für Festkörperforschung, Stuttgart (Prof. B. Keimer)
- University of Tübingen, Germany (Prof. R. Kleiner, Prof. D. Kölle)
- University of Würzburg, Germany (Prof. W. Hanke, Prof. F. Assaad, Prof. C. Honerkamp, Dr. M. Potthoff)
- University of Augsburg, Germany (Dr. S. Kohler, Prof. Dr. P. Hänggi)
- Brandenburgisch-Technische Universität Cottbus, Germany (Prof. D. Schmeißer)
- University of Hamburg, Germany (Dr. G. Meier, Prof. W. Wurth)
- Abt. Halbleiterphysik, University of Ulm, Germany (Dr. W. Limmer)
- RWTH Aachen, Germany (Dr. B. Beschoten)
- Universität Duisburg-Essen, Germany (Dr. A. Ney)
- Universität Bielefeld, (Dr. A. Thomas)
- University of British Columbia, Vancouver, Kanada (Prof. D. Bonn, Prof. A. Damascelli)
- Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany (Prof. F. Steglich)
- Walter Schottky Institut, TU München, Germany (Prof. G. Abstreiter, Prof. J. Finley, Dr. M. Brandt, Dr. D. Bougeard, Prof. A. Holleitner)
- Ludwig-Maximilians-Universität München, Germany (Prof. J.P. Kotthaus, Prof. J. von Delft, Prof. E. Frey, Prof. T. Franzosch, Prof. J. Rädler, Dr. F. Marquardt, Dr. B. Nickel)
- Lehrstuhl E10, Physik Department, TU München, Germany (Prof. D. Grundler)
- University of Birmingham, UK (Prof. E.M. Forgan)
- Paul Scherrer Institute, ETH Zürich (Prof. Joel Mesot)
- University of Geneva, Switzerland (O. Fischer)
- HMI Berlin, Germany (Dr. A. Buchsteiner, Dr. J. Pieper, Dr. K. Siemensmeyer)
- Royal Holloway University, London UK (Prof. J. Saunders)
- University of Liverpool, UK (Dr. J. Goff)
- CNRS Grenoble, France (Prof. H. Godfrin)
- University of Florida, USA (Prof. D. Adams, Prof. Y. Takano)
- Technische Universität, München (Prof. P. Böni, Prof. F. von Feilitzsch, Prof. A. Holleitner, Prof. F.C. Simmel, Dr. S. Dunsiger)
- Universidad de Zaragoza, Spain (Prof. L. Morellon, Prof. J.M. de Teresa)
- EPFL Lausanne, Switzerland (Prof. H. Ronnov)
- University of New South Wales, Sydney, Australia (M. Simmons)
- BMW Group, Munich, Germany (Dr. J. Schnagl)
- Siemens AG, CT MM 2, Munich, Germany (Dr. R. Matz)
- Attocube, Munich, Germany

- Concentris GmbH, Basel, Switzerland
- BASF AG, Mannheim, Germany
- THEVA Dünnschichttechnik, Ismaning, Germany (Dr. W. Prusseit)
- Fa. Egomedical AG, Munich
- Fa. Süss Micro Tec GmbH, Munich

Research visits

Extended visits of members of the Walther-Meißner-Institute at other research laboratories:

1. **Anton Lerf**
Instituto de Ciencia de Materiales de Sevilla, Spain
17. 03. - 25. 03. 2009, 05. 06. - 10. 06. 2009
2. **Mark Kartsovnik, Toni Helm**
High Magnetic Field Laboratory Grenoble, France
08. 11. - 16. 11. 2009
3. **Toni Helm**
High Magnetic Field Laboratory, Dresden
06. 09. - 19. 09. 2009
4. **Toni Helm, Werner Biberacher**
High Magnetic Field Laboratory, Toulouse, France
29. 11. - 04. 12. 2009
5. **Bianca Hermann**
Institute of Inorganic Chemistry, Dept. of Chemistry, University of Basel
24. 02. - 26. 02. 2009
6. **Rudolf Hackl**
Hungarian Academy of Sciences and Budapest University of Technology and Economics,
Budapest, Hungary
16. 01. - 21. 01. 2009
7. **Rudolf Hackl**
Stanford University, Stanford, CA, USA
05. 06. - 24. 06. 2009, 29. 09. - 15. 10. 2009
8. **Rudolf Hackl**
State University of New York, USA
15. 10. - 20. 10. 2009
9. **Hans-Martin Eiter, Bernhard Muschler**
Stanford University, Stanford, CA, USA
08. 10. - 19. 10. 2009

Conference Talks and Seminar Lectures

Bea Botka

1. **Raman scattering study of functionalized carbon nanotubes**
Meeting of the EU Marie Curie project (FINELUMEN), Gent Belgium
22. 10. 2009

Frank Deppe

1. **Two-photon probe of the Jaynes-Cummings model and controlled symmetry breaking in circuit QED**
APS March Meeting, Pittsburgh Pennsylvania, USA
16. - 20. 03. 2009
2. **Two-photon probe of the Jaynes-Cummings model and controlled symmetry breaking in circuit QED**
International Summer School and Workshop on Solid-State Quantum Information Processing, Herrsching, Germany
28. 06. - 03. 07. 2009
3. **Experimental circuit quantum electrodynamics with superconducting qubits**
International Workshop (QISSS), Bilbao, Spain
05. - 07. 08. 2009

Dietrich Einzel

1. **Theory of Superconductivity for Experimentalists**
Oberseminar über Festkörperphysik, Kirchhoff-Institut für Physik, Universität Heidelberg, Germany
20. 11. 2009

Hans-Martin Eiter

1. **Charge Density Waves in $R\text{Te}_3$**
Stanford University, Stanford, CA, USA
08. 10. 2009

Andreas Erb

1. **Crystal growth of the high temperature superconductors: from Cuprates to Pnictides**
Rutherford Appleton Laboratory (RAL), UK
24. 11. 2009

Sebastian Gönnerwein

1. **Magnetoelastic magnetization manipulation in ferromagnet/ferroelectric hybrids**
Hauptseminar Nanoelektronik, Technische Universität München, Germany
14. 05. 2009
2. **Spin Physics in ZnO-based Hybrid Structures**
Workshop of the Priority Program 1285, Technische Universität München, Germany
28. 05. 2009
3. **Magnetization Control in Multifunctional Heterostructures**
Euromat 2009, Glasgow, Scotland
09. 09. 2009

4. **Spin Mechanics – Magnetoelastic magnetization manipulation in ferromagnet/ferroelectric hybrids**
 IFF Seminar, Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden, Germany
 16. 11. 2009

Rudolf Gross

1. **Superconducting Quantum Circuits: From New Regimes in Quantum Optics to Quantum Information Processing**
 invited talk, 429th WE-Heraeus-Seminar on “Microwaves for Condensed Matter Physics”
 April 05–08, 2009, Bad Honnef, Germany.
2. **Quantum Experiments and Information Processing Based on Solid-State Nanostructures**
 invited talk, NanoDays 2009,
 May 06, 2009, Copenhagen, Denmark.
3. **Superconducting Quantum Circuits**
 invited tutorial, European School on Superconductivity,
 June 21 – 26, 2009, Lans en Vercors, France.
4. **Revealing the Fermi Surface of $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ by Magnetic Quantum Oscillations**
 invited talk, International Conference on Magnetism,
 July 26 – 31, 2009, Karlsruhe, Germany.
5. **Superconducting Quantum Circuits**
 invited talk, International Conference on Vortex Matter in Nanostructured Superconductors (VORTEX VI)
 September 17 – 24, 2009, Rhodes, Greece.
6. **Cross-correlation Detection of Weak Microwave Signals: Vacuum Fluctuations and Variance of Nontrivial Propagating Signals**
 invited talk, 445th Wilhelm und Else Heraeus Seminar on Quantum Measurement and Metrology with Solid State Devices
 November 01 – 05, 2009, Bad Honnef, Germany.
7. **Pulsed Laser Deposition of Complex Oxides: Playing LEGO on an Atomic Scale**
 R. Gross
 invited talk, 5th DAE-BRNS International Symposium on Pulsed Laser Deposition of Thin Films and Nanostructured Materials
 December 02 – 04, 2009, Chennai, India.
8. **Probing the Bounds of Possibility: Ultra-Low Temperature Experiments at the Quantum Limit**
 R. Gross
 invited talk, PTB-Symposium on “Physics and Metrology at Very Low Temperatures”
 December 10, 2009, Berlin, Germany.
9. **Quantum Optics on a Chip**
 R. Gross
 09. 06. 2009
 Colloquium of the Max-Planck-Instituts für Quantenoptik, Garching, Germany.
10. **Superconducting Quantum Circuits**
 R. Gross
 27. 10. 2009
 Physikalisches Kolloquium, Universität Konstanz, Germany.
11. **Kalt, kälter, Tieftemperaturforschung am Walther-Meißner-Institut**
 R. Gross
 16. 11. 2009
 Annual Meeting of the Gesellschaft der Freunde der Bayerischen Akademie der Wissenschaften, München, Germany.

12. From Mechanical to Quantum Mechanical Information Processing — Superconducting Quantum Circuits and Quantum Optics on a Chip

R. Gross

08. 12. 2009

Indian Institute of Technology Madras, Chennai, India.

Rudolf Hackl

1. Momentum-resolved electronic Raman scattering

EU project (FINELUMEN), Strasbourg, France

29. 04. 2009

2. Electron-electron interaction and gap nodes in FeAs superconductors

Stanford University, Stanford, CA, USA

16. 06. 2009

3. Electron interactions and gap nodes in FeAs superconductors

Kavli Institute for Theoretical Physics, Santa Barbara, CA, USA

18. 06. 2009

4. The gap in FeAs superconductors: who is right and what can we learn?

University of Konstanz, Germany

13. 08. 2009

5. The mysterious second energy gap in the cuprates

Stanford University, Stanford, CA, USA

10. 10. 2009

6. Is the energy gap a defining quantity of superconductors?

State University of New York, USA

16. 10. 2009

7. Electron dynamics in BaFe₂As₂ superconductors

Karlsruhe Institute of Technology, Karlsruhe, Germany

19. 11. 2009

Bianca Hermann

1. Predicting Molecular Pattern Diversity: Elementary Geometrical Features Encoding Molecular Ordering

Electron Controlled Chemical Lithography (ECCL) 2009, Istanbul, Turkey

05. 06. 2009

2. Molecular Surfaces: STM-Probing, Simulation and Application to Organic Superconductors and Protein Detection

Institute for Nanoelectronics, Dept. of Electrical Engineering, TU München, Germany

25. 06. 2009

Elisabeth Hoffmann

1. Two Resonator Circuit QED: A Superconducting Quantum Switch

Spring Meeting of the German Physical Society, Dresden, Germany

22. 03. - 27. 03. 2009

Hans Hübl

1. News on an old donor: Strategies for single phosphorus donor readout

University of Oxford, United Kingdom

10. 06. 2009

2. **News on an old donor: Strategies for single phosphorus donor readout**
Festkörperkolloquium, Fakultät für Physik, TU München, Germany
19. 11. 2009

Mark Kartsovnik

1. **Revealing the Fermi surface of $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ by high-field magnetotransport**
Spring Meeting of the German Physical Society, Dresden, Germany
22. 03. - 27. 03. 2009
2. **Magnetic quantum oscillations in the electron-doped superconducting cuprate $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$: evidence for the doping-induced evolution of the Fermi surface**
9th International Conference on Research in High Magnetic Fields, RHMF 2009, Dresden
22. - 25. 07. 2009
3. **Does Magnetic Field Break the Interlayer Coherence**
VIIIth International Symposium on Crystalline Organic Metals, Superconductors and Magnets, ISCOM 2009, Hokkaido, Japan
12. - 17. 09. 2009
4. **Probing the Fermi surface of an electron-doped cuprate superconductor by high field magnetotransport**
I.F. Schegolev Memorial Conference "Low-Dimensional Metallic and Superconducting Systems", Chernogolovka, Russia
11. - 16. 10. 2009
5. **Quantum and semiclassical oscillations of magnetoresistance in an electron-doped cuprate superconductor**
EuroMagNET II user meeting, Nijmegen, The Netherlands
29. 11. 2009
6. **Field-induced dimensional crossover in the conductivity of $\alpha\text{-(ET)}_2\text{KHg(SCN)}_4$: does magnetic field break the interlayer coherence**
IPCP Seminar, Chernogolovka, Russia
29. 12. 2009

Anton Lerf

1. **Intercalation chemistry of clay minerals: past, presence and future**
Nanotechnology Centre, Technical University of Ostrawa
12. - 17. 10. 2009

Achim Marx

1. **Two-photon probe of the Jaynes-Cummings model and controlled symmetry breaking in circuit QED**
Spring Meeting of the German Physical Society, Dresden, Germany
22. 3. - 27. 03. 2009
2. **Cross-correlation heterodyne detection: Measuring microwave nontrivial propagating signals**
Spring Meeting of the German Physical Society, Dresden, Germany
22. 03. - 27. 03. 2009

Edwin Menzel

1. **Cross-correlation heterodyne detection part II: Measuring microwave nontrivial propagating signals**
APS March Meeting 2009, Pittsburgh, Pennsylvania, USA
19. 03. 2009

2. **Cross-correlations of vacuum fluctuations and variance of propagating microwave signals**
International Workshop on Quantum Information and Solid-State Systems (QISSS), Bilbao, Spain
07. 08. 2009
3. **Cross-Correlation Measurements of Vacuum Fluctuations and Variance of Propagating Microwave Signals**
Kryoelektronische Bauelemente 2009, Oberhof, Germany
04. 10. - 06. 10. 2009
4. **Cross-Correlation Measurements of the First Two Moments of Propagating Microwave Signals**
Advances in Solid-State Physics, Walther-Meissner-Institut, Garching
17. 11. 2009

Bernhard Muschler

1. **Raman Scattering in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$: metal-insulator transition and quantum criticality**
Spring Meeting of the German Physical Society, Dresden, Germany
25. 03. 2009
2. **Doping dependence of the electronic properties of the Iron Arsenides**
Stanford University, Stanford, CA, USA
08. 10. 2009

Tomasz Niemczyk

1. **Vacuum Rabi splitting and microwave spectroscopy of flux qubits coupled to a coplanar-waveguide resonator**
Kryoelektronische Bauelemente 2009, Oberhof, Germany
04. 10. - 06. 10. 2009

Matthias Opel

1. **Ferromagnetism or magnetic clusters in cobalt-substituted ZnO**
Colloquium of the Collaborative Research Center 445, Universität Duisburg-Essen
16. 07. 2009
2. **Neue funktionale Schichtsysteme auf der Basis künstlicher heteroepitaktischer Mehrlagenstrukturen aus Übergangsmetalloxiden**
Colloquium of the Priority Program 1157, Bonn, Germany
21. 09. 2009
3. **Multifunctional materials based on oxide thin film structures**
Instituto de Nanociencia de Aragon, Universidad de Zaragoza, Spain
02. 10. 2009
4. **Is cobalt-substituted ZnO a dilute magnetic semiconductors?**
Nano-DIEB-Seminar, Brandenburgisch-Technische Universität Cottbus
16. 11. 2009

Erwin Schuberth

1. **Magnetization Measurements on YbRh_2Si_2 at Very Low Temperatures**
Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden
27. 05. 2009

Lectures, Seminars, Courses and other Scientific Activities

Lectures

A: Technische Universität München

Dietrich Einzel

- | | |
|--------------|---|
| WS 2008/2009 | <ul style="list-style-type: none"> • Mathematische Methoden der Physik I (Mathematical Methods of Physics I) • Übungen zu Mathematische Methoden der Physik I (Mathematical Methods of Physics I, Problem Sessions) • WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid State Physics, with R. Gross, S.B.T. Gönnerwein, A. Marx, M. Opel, R. Hackl) |
| SS 2009 | <ul style="list-style-type: none"> • Mathematische Methoden der Physik II (Mathematical Methods of Physics II) • Übungen zu Mathematische Methoden der Physik II (Mathematical Methods of Physics II, Problem Sessions) • WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, S.B.T. Gönnerwein, A. Marx, M. Opel, R. Hackl) |
| WS 2009/2010 | <ul style="list-style-type: none"> • Mathematische Methoden der Physik I (Mathematical Methods of Physics I) • Übungen zu Mathematische Methoden der Physik I (Mathematical Methods of Physics I, Problem Sessions) • WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, S.B.T. Gönnerwein, H. Hübl, A. Marx, M. Opel, R. Hackl) |

Rudolf Gross

- | | |
|--------------|--|
| WS 2008/2009 | <ul style="list-style-type: none"> • Einführung in die Festkörperphysik (Introduction to Solid-State Physics) • Tutorium zur Einführung in die Festkörperphysik (Introduction to Solid-State Physics, Tutorium) • Übungen zur Einführung in die Festkörperphysik (Introduction to Solid-State Physics, Problem Sessions, with D. Einzel) • Angewandte Supraleitung (Applied Superconductivity, with A. Marx) • WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with D. Einzel, S.B.T. Gönnerwein, A. Marx, M. Opel, R. Hackl) |
|--------------|--|

- Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)
- Festkörperkolloquium (Colloquium on Solid-State Physics, with D. Einzel)
- SS 2009
 - Festkörperphysik II (Solid-State Physics II)
 - Tutorium zur Festkörperphysik II (Solid-State Physics II, Tutorium)
 - Übungen zur Festkörperphysik II (Solid-State Physics II, Problem Sessions, with D. Einzel)
 - Proseminar Physik/Technik: Makroskopische Quantenphänomene (Introductory Seminar Course Engineering/Physics: Macroscopic Quantum Phenomena, with S. Dunsiger, Ch. Pfeleiderer, R. Hackl, S.T.B. Gönnerwein, A. Marx, M. Opel)
 - Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)
 - Festkörperkolloquium (Colloquium on Solid-State Physics, with D. Einzel)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with D. Einzel, S.B.T. Gönnerwein, A. Marx, M. Opel, R. Hackl)
- WS 2009/2010
 - Angewandte Supraleitung (Applied Superconductivity, with A. Marx)
 - Supraleitung und Tieftemperaturphysik I (Superconductivity and Low Temperature Physics I, with R. Hackl)
 - Übungen zu Supraleitung und Tieftemperaturphysik I (Superconductivity and Low Temperature Physics I, Problem Sessions, with R. Hackl)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with D. Einzel, S.B.T. Gönnerwein, A. Marx, M. Opel, R. Hackl)
 - Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)
 - Festkörperkolloquium (Colloquium on Solid-State Physics, with D. Einzel)

Sebastian T.B. Gönnerwein

- WS 2008/2009
 - Magnetismus (Magnetism)
 - Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, D. Einzel, A. Marx, M. Opel, R. Hackl)
 - Seminar zu aktuellen Fragen der Magneto- und Spinelektronik (Seminar on Current Topics in Magneto and Spin Electronics, with M. Brandt, M. Opel)
- SS 2009
 - Magnetoelektronik mit Tutorial
 - Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)

- WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, D. Einzel, A. Marx, M. Opel, R. Hackl)
- Seminar zu aktuellen Fragen der Magneto- und Spinelektronik (Seminar on Current Topics in Magneto and Spin Electronics, with M. Brandt, M. Opel)
- WS 2009/2010
 - Seminar on Advances in Solid-State Physics (with S.T.B. Gönnerwein, R. Hackl, H. Hübl, M. Opel, A. Marx)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid State Physics, with R. Gross, D. Einzel, H. Hübl, A. Marx, M. Opel, R. Hackl)
 - Seminar zu aktuellen Fragen der Magneto- und Spinelektronik (Seminar on Current Topics in Magneto and Spin Electronics, with M. Brandt, M. Opel)

Rudi Hackl

- WS 2008/2009
 - Supraleitung und Tieftemperaturphysik I (Superconductivity and Low Temperature Physics I, with R. Gross)
 - Problems and Solution in Superconductivity (with D. Einzel)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, S.B.T. Gönnerwein, A. Marx, M. Opel, D. Einzel)
- SS 2009
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, S.B.T. Gönnerwein, H. Hübl A. Marx, M. Opel, D. Einzel)
 - Proseminar Physik/Technik: Makroskopische Quantenphänomene (Introductory Seminar Course in Physics/Engineering: Macroscopic Quantum Phenomena, with S. Dunsiger, S.T.B. Gönnerwein, R. Gross, A. Marx, M. Opel, C. Pfeiderer)
 - Seminar: Many-body effects and scattering methods (with C. Pfeiderer, W. Zwerger)
- WS 2009/2010
 - Supraleitung und Tieftemperaturphysik I (Superconductivity and Low Temperature Physics I, with R. Gross)
 - Problems and Solutions in Superconductivity (with D. Einzel, R. Gross)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid-State Physics, with R. Gross, S.B.T. Gönnerwein, H. Hübl, A. Marx, M. Opel, D. Einzel)
 - Seminar: Experimental methods and electronic correlations (with C. Hugenschmidt and C. Pfeiderer)
 - Seminar on Advances in Solid-State Physics (with R. Gross, S.T.B. Gönnerwein, H. Hübl, A. Marx, M. Opel)

Hans Hübl

- WS 2009/2010
- Seminar on Advances in Solid-State Physics (with R. Gross, D. Einzel, S.T.B. Gönnerwein, A. Marx, M. Opel)
 - WMI-Seminar über aktuelle Fragen der Tieftemperatur-Festkörperphysik (WMI Seminar on Current Topics of Low Temperature Solid State Physics, with R. Gross, D. Einzel, S.T.B. Gönnerwein, A. Marx, M. Opel, R. Hackl)
 - Magnetismus (Magnetism, with S.T.B. Gönnerwein)
 - Tutorium to Magnetismus (Magnetism, Tutorium, with S.T.B. Gönnerwein)

Anton Lerf

- WS 2008/2009
- Moderne Aspekte der Chemie für Physiker I (Modern Aspects of Chemistry for Physicists I)
- SS 2009
- Moderne Aspekte der Chemie für Physiker I (Modern Aspects of Chemistry for Physicists I)
 - Nanostrukturierte Materie (Nanostructured Matter, with Prof. J. Plank)
- WS 2009/2010
- Moderne Aspekte der Chemie für Physiker I (Modern Aspects of Chemistry for Physicists I)
 - Stoffströme in Natur und Technik (Material Flow in Nature and Technology, with Prof. K. Köhler)

Erwin Schubert

- SS 2009
- Supraleitung und Tieftemperaturphysik II (Superconductivity and Low Temperature Physics II)

B: Ludwig-Maximilians Universität München**Bianca Hermann**

- WS 2008/2009
- PNI: Einführung in die Physik (für Chemie- und Biochemiestudierende)
 - Übungen zu PNI: Einführung in die Physik
 - Seminar über spezielle Fragen der Rastertunnelmikroskopie
 - Seminar über die aktuelle Literatur zu korrelierten Phänomenen insbesondere der molekularen Selbstorganisation und der Supraleitung
- SS 2009
- Moderne Rastersondenmikroskopie- und Spektroskopietechniken
 - Seminar über die aktuelle Literatur zu korrelierten Phänomenen insbesondere der molekularen Selbstorganisation und der Supraleitung
 - Seminar über spezielle Fragen der Rastertunnelmikroskopie

The WMI Seminars

The Friday Seminar –

Walther-Meißner-Seminar on Current Topics in Low Temperature Physics

1. **Strain-mediated magnetoelectric effects in hybrid multiferroic heterostructures**
Prof. Dr. N.A. Pertsev, A.F. Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia
23. 01. 2009
2. **Coherent oscillations in a superconducting tunable flux qubit manipulated without microwaves**
Dr. Stefano Poletto, Physikalisches Institut, Universität Karlsruhe
30. 01. 2009
3. **Intermediate Coupling Model of the Cuprate Phase Diagram**
Prof. Dr. Robert Markiewicz, Northeastern University, Boston, USA
24. 04. 2009
4. **Coupling superconducting qubits using sideband transitions in circuit QED**
Dr. Peter Leek, Laboratorium für Festkörperphysik, ETH Zürich
08. 05. 2009
5. **Aspects of single crystal growth from flux**
Dr. Thomas Wolf, Forschungszentrum Karlsruhe
15. 05. 2009
6. **Microwave spectroscopy detected by thermal near field microscopy: resolution in nanometer range**
Dr. Ralf Meckenstock, Universität Duisburg-Essen
19. 06. 2009
7. **Quasi-2D organic conductors κ -(ET)₂X studied by fluctuation spectroscopy a new approach to the dynamics of correlated pi-electrons**
Prof. Dr. Jens Müller, Physikalisches Institut, Johann-Wolfgang-Goethe-Universität, Frankfurt am Main
03. 07. 2009
8. **Multiferrocity and critical behavior of MnWO₄ and Cu₂OSeO₃**
Prof. Dr. Peter Lemmens, Institute for Condensed Matter Physics, Technische Universität, Braunschweig
10. 07. 2009
9. **Phase and spin dynamics in ferromagnetic Josephson junctions**
Dr. Marco Aprili, Laboratoire de Physique des Solides, Université Paris-Sud
17. 07. 2009
10. **Superconducting atom-chip: cold atoms in a cryogenic environment and excitation of Rydberg atoms**
Dr. Andreas Emmert, Laboratoire Kastler Brossel, Département de Physique de l'E.N.S., Paris, France
24. 07. 2009
11. **Heusler compounds: materials for spintronic devices**
Dr. Andy Thomas, Universität Bielefeld
07. 08. 2009
12. **Relativistic quantum simulations in quantum optics and circuit QED**
Prof. Dr. Enrique Solano, Departamento de Química Física, Universidad del País Vasco - Euskal Herriko Unibertsitatea, Bilbao, Spain
13. 11. 2009
13. **Magnetotransport of coupled quantum Hall edges in a bent quantum well**
Dr. Lucia Steinke, Walther-Meißner-Institut, Garching
20. 11. 2009

14. **Giant magnetoresistance in (electro-deposited) magnetic nanostructures**
Dr. Imre Bakonyi, Hungarian Academy of Sciences, Budapest, Hungary
04. 12. 2009
15. **Superconducting Pairing in the Iron Pnictides**
Dr. Siegfried Graser, Institut für Physik, Universität Augsburg
11. 12. 2009

Topical Seminar on Advances in Solid State Physics – WS 2008/2009, SS 2009 and WS 2009/2010

1. **Introduction, presentation of seminar topics for WS 2008/2009, and assignment of topics to interested students**
Rudolf Gross, Walther-Meißner-Institut
14. 10. 2008
2. **Magnetisierungsmessungen an dem Schwere-Fermionen-System YbRh_2Si_2 bei ultratiefen Temperaturen**
Marc Tippmann, Walther-Meißner-Institut
28. 10. 2008
3. **Two-Resonator Circuit QED: A Superconducting Quantum Switch**
Elisabeth Hoffmann, Walther-Meißner-Institut
04. 11. 2008
4. **Superconducting Quantum Circuits: Building Blocks for cQED experiments**
Thomas Niemczyk, Walther-Meißner-Institut
11. 11. 2008
5. **Playing with the Microwave Vacuum and Measuring its Covariance Matrix**
Matteo Mariani, Walther-Meißner-Institut
18. 11. 2008
6. **Kuprate beim Einsatzpunkt der Supraleitung**
Bernhard Muechler, Walther-Meißner-Institut
25. 11. 2008
7. **Spintronics based on the wide bandgap semiconductor zinc oxide**
Matthias Althammer, Walther-Meißner-Institut
09. 12. 2008
8. **Die neuen FeAs-Supraleiter: Experimenteller Status und Stand der Forschung**
Reinhard Roßner, Technische Universität, München
16. 12. 2008
9. **Materialien mit negativem Brechungsindex**
Christian Siebenwirth, Technische Universität München
13. 01. 2009
10. **Erzeugung von Mikrowellen-Fock-Zuständen mit supraleitenden Quantenschaltkreisen**
Christian Heeg, Technische Universität München
20. 01. 2009
11. **Der Spin-Hall-Effekt**
Alexander Krupp, Technische Universität München
27. 01. 2009
12. **Surface acoustic waves at piezoelectric/ferromagnetic interfaces**
Mathias Weiler, Walther-Meißner-Institut
03. 02. 2009
13. **Quantenexperimente mit elektromagnetischen Systemen**
Fredrik Hocke, Walther-Meißner-Institut
10. 02. 2009
14. **Kontrolle der Magnetisierung in multifunktionalen Hybridsystemen durch elektrische Felder**
Andreas Brandlmaier, Walther-Meißner-Institut
17. 02. 2009
15. **Transport measurements in 214-high-temperature-superconductors**
Toni Helm, Walther-Meißner-Institut

03. 03. 2009

16. **Introduction, presentation of seminar topics for SS 2009**
Rudolf Gross, Walther-Meißner-Institut
28. 04.2009
17. **Peltier-Kühler mit schweren Fermionen**
Karl Neumaier, Walther-Meißner-Institut
05.05.2009
18. **Magneto-Optics in Ferromagnets**
Matthias Brasse, Walther-Meißner-Institut
12.05.2009
19. **Parametrische Verstärker für quantenlimitierte Messungen**
Max Balbach, Technische Universität München
19.05.2009
20. **Herstellung, Charakterisierung und Untersuchung hochgeordneter Y-123-Einkristalle**
Timo Buttler, Walther-Meißner-Institut
26. 05. 2009
21. **Molekulare Spintronik**
Martin Radlmeier, Technische Universität München
16. 06. 2009
22. **Quantenoptik auf einem Chip**
Thomas Günthner, Technische Universität München
23. 06. 2009
23. **Winkelaufgelöste Magnetotransportmessungen in polykristallinen dünnen Schichten**
Michael Wagner, Walther-Meißner-Institut
14. 07. 2009
24. **Optimierung und Charakterisierung von supraleitenden Quantenschaltkreisen auf der Basis von Fluss-Quantenbits**
Lars Eggenstein, Walther-Meißner-Institut
21. 07. 2009
25. **Optomechanik: Untersuchung und Kühlung nanomechanischer Oszillatoren mittels Mikrowellen**
Thomas Selle, Technische Universität München
04. 08. 2009

26. **Preliminary discussion and assignment of topics**
Rudolf Gross, Walther-Meißner-Institut
20. 10. 2009
27. **Ladungsdichtewellen in $R\text{Te}_3$ ($R = \text{La, Dy, ...}$)**
Hans-Martin Eiter, Walther-Meißner-Institut
03. 11. 2009
28. **Hochfrequente mechanische Verspannung und Magnetotransporteigenschaften von ferromagnetischen Dünnschichtstrukturen**
Christian Heeg, Technische Universität München
10. 11. 2009
29. **Cross-Correlation Measurements of the First Two Moments of Propagating Microwave Signals**
Edwin Menzel, Walther-Meißner-Institut
17. 11. 2009
30. **Generation of Arbitrary Quantum States in a Superconducting Resonator**
Peter Eder, Technische Universität München
24. 11. 2009
31. **Superconductivity without Electron-Phonon Interaction**
Christoph Rathgeber, Technische Universität München
01. 12. 2009
32. **Methods of Crystal growth from melts and solutions**
Christian Wachauf, Technische Universität München

08. 12. 2009

33. **Optomechanics**

Max Rietzl, Technische Universität München

15. 12. 2009

34. **Tunable Tunneling Barriers**

Alexander Kaiser, Technische Universität München

12. 01. 2010

35. **Physics of Interfaces in Oxide Heterostructures**

Marta Krawczyk, Technische Universität München

19. 01. 2010

36. **Light Propagation in Metals**

Felix Bilger, Technische Universität München

19. 01. 2010

37. **Superconducting Group-IV Semiconductors**

Michael Puls, Technische Universität München

26. 01. 2010

38. **Topological Insulators**

Stefan Beer, Technische Universität München

02. 02. 2010

39. **Multiferroic Magnetoelectronic Composites: Foundations and Applications**

Roberta Kriegl, Technische Universität München

09. 02. 2010

C: Solid State Colloquium

The WMI has organized the Solid-State Colloquium of the Faculty of Physics in WS 2008/2009, SS 2009, and WS 2009/2010. The detailed program can be found on the WMI webpage: <http://www.wmi.badw-muenchen.de/teaching/Seminars/fkkoll.html>

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Assistants

Sybilla Plöderl

Brigitte Steinberg

Permanent Guests

Prof. Dr. B. S. Chandrasekhar

Dr. Robert Doll

Dr. Karl Neumaier

Dr. Christian Probst

Prof. Dr. Schöllhorn

Guest Researchers

1. Prof. Dr. B.S. Chandrasekhar
permanent guest
2. Dr. Robert Doll
permanent guest
3. Dr. Karl Neumaier
permanent guest
4. Dr. Christian Probst
permanent guest
5. Prof. Dr. Robert Schöllhorn
permanent guest
6. Dr. Nataliya D. Kushch, Institute of Problems of Chemical Physics, Chernogolovka, Russia
12. 01. - 11. 03. 2009
7. Dr. Sergej Pesotskii, Institute of Problems of Chemical Physics, Chernogolovka, Russia
12. 01. - 11. 03. 2009
8. Dr. Oleg Vyaselev, Institute of Solid Physics, Chernogolovka, Russia
19. 04. - 18. 06. 2009
9. Dr. M. Lavagnini, ETH Zürich
21. - 24. 04., 20. - 23. 05., 26. - 30. 07. 2009
10. Dr. Pavel Grigoriev, Landau Institute, Chernogolovka, Russia
22. 04. - 25. 04. 2009, 20. 10. - 24. 10. 2009
11. Prof. Dr. Suneel Srivastava, Indian Institute of Technology, Kharagpur, India
11. 05. - 04. 07. 2009
12. Prof. Vladimir Zverev, Institute of Solid Physics, Chernogolovka, Russia
22. 06. - 02. 08. 2009, 23. 11. - 23. 12. 2009
13. Prof. Dr. Juan Poyato Ferrera, Instituto de Ciencia de Materiales, Sevilla, Spain
01. 07. - 31. 07. 2009
14. Prof. Dr. I. Tüttö, Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences Budapest, Hungary
02. 08. - 09. 08. 2009
15. Prof. Alfred Zawadowski, Budapest University of Technology and Economics, Budapest, Ungarn
02. 08. - 09. 08. 2008
16. M. Sc. Hajnalka-Mária Tóháti, Hungarian Academy of Sciences, Budapest, Ungarn
25. 09. - 02. 10. 2009

Commission for Low Temperature Physics

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