TECHNISCHE UNIVERSITÄT DRESDEN

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Complexity and Topology in Quantum Matter

Abstract Booklet

Workshop „Nanoscale Quantum Materials“

Virtual workshop on Zoom

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Prof. Artem Mishchenko
University oft Manchester, UK

Title:
Programmable van der Waals materials

Abstract:
I will present our recent progress in quantum properties programmable on-demand in the rapidly growing field of van der Waals materials. The advent of Van der Waals technology has allowed the development of many materials that did not exist before and has led to the observation of many exciting new physical phenomena in these materials due to the unique electronic, optical and mechanical properties of 2D atomic crystals. In particular, I will discuss how interlayer twist angle and stacking order can be used for deterministic control of the properties of van der Waals materials. Tuning twist angle (twistronics) became recently a huge field since electronic bands of 2D materials, their nontrivial topology, electron-electron interactions, and other structural and electronic degrees of freedom can be dramatically changed by a moiré pattern induced by twist angles between different layers. On the other hand, control of the stacking order provides an alternative approach to program quantum properties, and without the need of a moiré superlattice. Controlling stacking order in multilayer graphite films allowed us to discover the quantum Hall effect in hexagonal graphite and to find strong electronic correlations in rhombohedral graphite films.

Prof. Floriana Lombardi
Chalmers University of Technology

Title:
Solving the puzzle of High critical temperature superconductors:
quantum effects in nanoscale devices

Abstract:
The understanding of the microscopic origin of High critical Temperature Superconductors (HTSs) cuprates still remains one of the grand challenges in solid state physics. These materials are dominated by strong correlations which lead to a normal state that cannot be described by traditional Fermi liquid theory.

The high critical temperature superconductivity in cuprates emerges from doping of a Mott insulator. The phase diagram is complex and dominated by a ”strange metal phase”. This state manifests in transport as a linear temperature behaviour of the resistivity, at the optimal doping, and in spectroscopy as the absence of quasiparticle excitations, signatures of a Fermi liquid. The strange metal phase is also confined by a mysterious doping and temperature dependent pseudogap regime, characterized by various local orders and symmetry breaking states, like *Charge Density Waves, local magnetism, and nematicity*. The local orders are intertwined in a very complex way, and the understanding of their interplay is instrumental for an insight into the high critical temperature phenomenon as a whole. The superconducting state appears, at a first sight, simpler: it is dominated by an unconventional d-wave order parameter. However, this order parameter alone is not enough to give hints about the HTS microscopic mechanism. Subdominant order parameters with different symmetries, as well as a pair density wave scenario where Cooper Pair have a finite momentum appear crucial ingredients to be included to properly address the cuprates' superconducting physics.

In this talk I will review our experiments on HTS nanoscale devices showing how they can be decisive to get new insights into the unconventional superconducting state as well as the “strange normal metal phase” of the cuprates.

The intrinsic presence of nodal quasiparticle even at T=0, inherent to the d-wave order parameter in cuprates, are supposed to induce dissipation that would prevent the observation of macroscopic quantum phenomenon in nanoscale Josephson devices. I will show instead that in HTS Josephson junctions, macroscopic quantum tunneling [1] and energy level quantization [2] can be detected. Moreover, by using an HTS single electron transistor, made of YBCO, as an extremely sensitive spectrometer, I will show that an imaginary component of the order parameter, adding on to the d-wave symmetry, has to be included to properly describe the superconducting condensate [3]. The resulting order parameter becomes therefore fully gapped and compatible with the observation of macroscopic quantum effects.

Because of the complexity of the HTS problem we have recently developed a research approach which can help to simplify the physics at play. If the bulk system is so complex by reducing the dimensionality, like in nm thick films and nanowires, the effect of charge, spin and nematic orders is enhanced, which can possibly lead to a simpler picture of the physics at play. In the final part of my presentation I will therefore present our efforts in building up a HTS thin films [4] and nanowires[5] platform where strain induced effects and reduced dimensionality allows to strongly modify the “strange metal phase” and more in general the phase diagram of the cuprates. The new physics we are disclosing is the result of a strategy that combines the information of transport properties at the nanoscale with synchrotron based spectroscopic technique like Resonant inelastic X-ray scattering [6]. This unique combination allows to reveal how the local orders like CDW are modified at the nanoscale and their effect on the physics of the nanodevices [7].

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Prof. Vojislav Krstic
Friedrich-Alexander-Universität Nürnber-Erlangen

Title:
Towards emergent quantum properties of nanoscaled materials

Abstract:
The quantum nature of materials and matter on the nanoscale can be disclosed by employing extreme thermodynamic conditions, diversification of the materials' intrinsic properties or by (structural) design.
In particular, specific properties of such quantum materials can be selectively targeted by according adjustment or combination of the aforementioned measures, revealing for instance the spinor-character of fermionic wavefunctions, the development of macroscopic and topologic quantum phases, quantum coherent charge transport or (chiral) anisotropic qualities.
To illustrate this powerful approach to surface the multifaceted quantum nature of materials on the nanoscale, several examples will be briefly discussed in selected materials (graphene, quantum nanowires, nanohelices) addressing light-like fermions, two-dimensional charge-density waves, the quantumness of charge transport (at room temperature) and cooperative and anisotropic responses of parity- and time-symmetry breaking systems.

Prof. Oleksandr Dobrovolskiy
University of Vienna, Austria

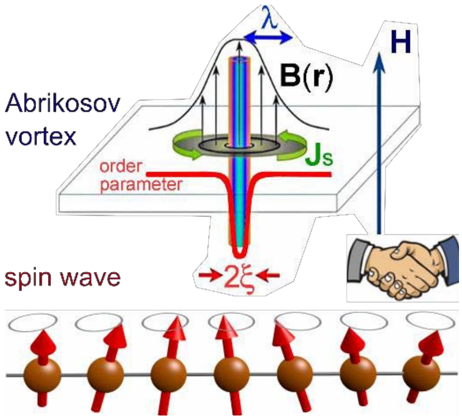
Title:
Coupled spin-wave and magnetic flux quanta in hybrid nanomaterials

Abstract:

Ferromagnetism and superconductivity belong to the most fundamental phenomena in condensed-matter physics. Recent discoveries in these topical areas enable the exploration of new physical phenomena at their interfaces. In this regard, interactions between the fundamental quasiparticles – magnetic flux quanta (fluxons) in superconductors and quanta of spin waves (magnons) in magnets – are especially fascinating. Nanoscale 2D and 3D hybrid materials offer unique platforms for experimental studies of such interactions [1].

In my talk, after a brief introduction of fluxons and magnons, I will focus on a set of our recent experimental findings. First, the magnon-fluxon interaction in ferromagnet/superconductor heterostructures was evidenced by spin-wave spectroscopy [2]. The array of vortices in the superconductor created a periodic scattering potential for spin waves propagating in the adjacent ferromagnet and induced Bloch-like bandgaps in the spin- wave transmission spectra. It was also demonstrated, that a rather slow (0.3 km/s) motion of vortices by the applied dc current results in the Doppler shift of the bandgap frequencies. Then, it became clear that an increase of the vortex velocity to at least 1 km/s should open access to new types of magnon-fluxon interactions. However, such high vortex velocities had not been available because of the escape of hot (un- paired) electrons from the vortex cores – the well-known phenomenon of flux-flow instability [3]. The modern direct-write nanofabrication by focused ion and electron beam-induced deposition (FIBID and FEBID) [4] allowed for the creation of a nano-engineered Nb-C superconductor with fast relaxation of heated electrons.

As a result, vortex velocities of up to 15 km/s have been achieved [5]. This has enabled the realization of the long-predicted theoretically, but so far never observed experimentally, phenomenon of Cherenkov radiation of magnons [6]. The magnon radiation has been detected in a Nb-C/Co-Fe hybrid structure by the current-voltage control of the superconductor and by the direct spin-wave detection using a microwave detection technique. The spin-wave excitation is unidirectional and monochromatic, with sub-40 nm wavelengths determined by the period of the vortex lattice. These findings set a stage for the new field of fluxon magnonics dealing with non-equilibrium coupled dynamics of quasiparticles in hybrid quantum nanomaterials.



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Dr. Matthias Althammer
Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching

Title:
Pure Spin Currents in Antiferromagnetic Insulators: Observation of the Magnon Hanle Effect

Abstract:

The spin-1/2 of an electron makes it an archetypal two-level system and inspires the description of other two-level systems using an analogous pseudospin. The quantized spin excitations of an ordered antiferromagnet are such pairs of spin-up and -down magnons and can be characterized by a magnonic pseudospin, which has eluded experiments thus far. The similarity between electronic spin and magnonic pseudospin has triggered the prediction of exciting phenomena like emergent spin-orbit coupling and topological states in antiferromagnetic magnonics. As a first step we will introduce the concept of magnon pseudospin and description of magnon pseudospin dynamics and discuss similarities to electron spin transport [1]. In the second part, we show our recent experiments demonstrating control of magnon spin transport and pseudospin dynamics in a 15 nm thin film of the antiferromagneticinsulator hematite (α-Fe_2O_3) utilizing two Pt strips for all-electrical magnon injection and detection [2]. We observe an oscillation in polarity of the magnon spin signal at the detector as a function of the externally applied magnetic field. We quantitatively explain our experiments in terms of diffusive magnon transport. In particular, we observe a coherent precession of the magnon pseudospin caused by the easy-plane anisotropy and the Dzyaloshinskii-Moriya interaction. This observation can be viewed as the magnonic analogue of the electronic Hanle effect and the Datta-Das transistor, unlocking the high potential of antiferromagnetic magnonics towards the realization of electronics-inspired phenomena.

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Prof. A.D. Caviglia
Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

Title:
Quantum materials design: electronic phase control by engineering interfaces and shining light

Abstract:
Exerting control over quantum materials is one of the main goals in condensed matter physics and is actively pursued using an ever expanding toolbox that includes interface engineering, nanofabrication and impulsive electromagnetic excitation. The overarching goal is to control macroscopic material properties, paving the way to new scientific insights and to future emerging technologies. We will discuss three examples of material control applied to topological phases, superconductivity and magnetism.

In the first example we will discuss the manipulation of topological charges at oxide interfaces. Three-dimensional strontium ruthenate ($SrRuO_3$) is an itinerant ferromagnet that features Weyl points acting as sources of emergent magnetic fields, anomalous Hall conductivity, and unconventional spin dynamics. Integrating $SrRuO_3$ in oxide heterostructures is potentially a novel route to engineer emergent electrodynamics, but its electronic band topology in the two-dimensional limit remains unknown. We will show that ultrathin $SrRuO_3$ exhibits spin-polarized topologically nontrivial bands at the Fermi energy. Their band anticrossings show an enhanced Berry curvature and act as competing sources of emergent magnetic fields. We control their balance by designing heterostructures with symmetric and asymmetric interfaces [1, 2].

In the second example we will discuss manipulating two-dimensional, dilute superconductivity in $SrTiO_3$-based heterostructures. We explore the gate-controlled superfluid density of the two-dimensional electron system at the $LaAlO_3/SrTiO_3$ interface by monitoring (i) the frequencies of the cavity modes of coplanar waveguide resonators [3] and (ii) the kinetic inductance of superconducting quantum interference devices [4,5] both fabricated in the interface itself. The extremely low superfluid density observed allows us to

fabricate electrostatically controlled Josephson junctions and one-dimensional channels in which the supercurrent is carried by a single quantized mode [6].

Finally we will consider the control of magnetic ordered states using light. We will show that light-driven phonons can be utilized to coherently manipulate macroscopic magnetic states. Intense mid-infrared electric field pulses tuned to resonance with a phonon mode of the archetypical antiferromagnet $DyFeO_3$ induce ultrafast and long-living changes of the fundamental exchange interaction between rare-earth orbitals and transition metal spins. Non-thermal lattice control of the magnetic exchange, which defines the stability of the macroscopic magnetic state, allows us to perform picosecond coherent switching between competing antiferromagnetic and weakly ferromagnetic spin orders [7,8].

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Prof. Steffen Wiedmann
High Field Magnet Laboratory (HFML-EMFL) and Institute for Molecules and Materials, Radboud University, Nijmegen, the Netherlands

Title:
Exploring Topological Matter under Extreme Conditions

Abstract:

Topology in condensed matter physics has become a thriving research field in the past two decades with the discovery of different classes of materials such as topological insulators, Weyl, Dirac and nodal-line semimetals (NLSMs). Experiments under extreme conditions such as low temperature and high magnetic fields play an important role to determine the charge carrier properties, Fermi surface, or peculiar phenomena that arise from the underlying band structure.

In my talk, I will present an example of my group's recent results on quantum oscillatory phenomena that occur in NLSMs in high magnetic fields up to 35 T with the focus on the compound ZrSiS [1,2]. The Fermi surface topology of ZrSiS is determined by means of de Haas–van Alphen and Shubnikov-de Haas quantum oscillations, which provides a full picture of its electronic ground state suggesting the presence of electronic correlations in this material [2,3]. The peculiar Fermi surface of this material class gives rise to a complex oscillation spectrum that evolves above a threshold magnetic field originating from individual electron and hole pockets as well as from magnetic breakdown between them in case the magnetic field is applied parallel to the *c*-axis of the crystals [2-4].

My group's future research will focus on searching for correlation effects in topological materials and vice versa. I will introduce experimental techniques such as transport under uniaxial strain and strain dilatometry, and electrostatic gating of thin films that we will employ to tune the fundamental properties of topological correlated matter using specific material platforms.

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