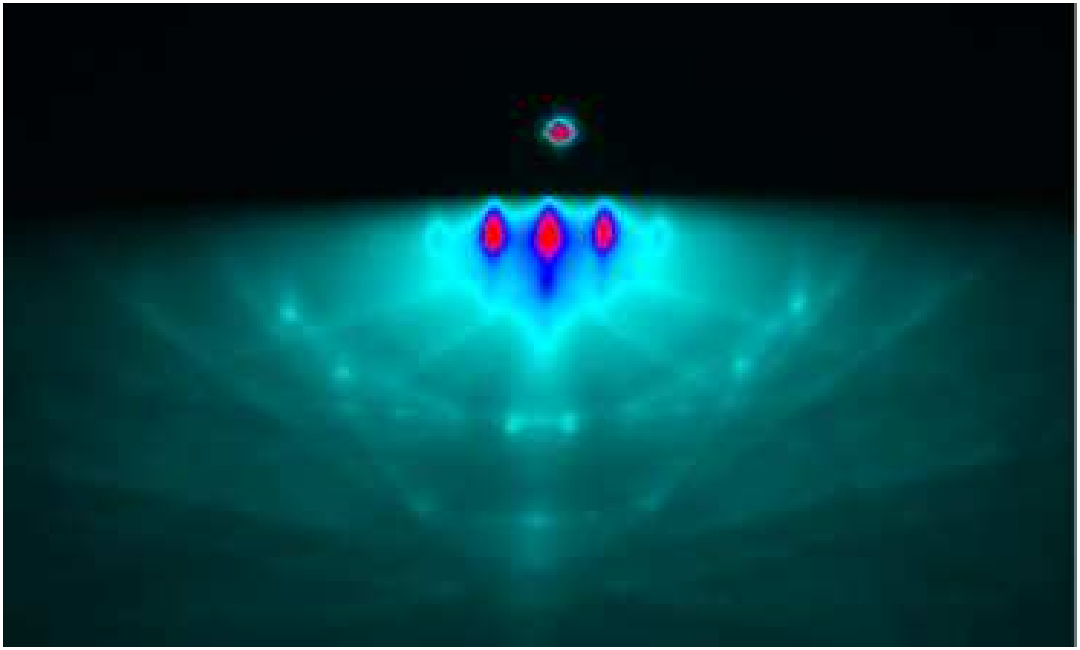
Condensed Matter Physics



Condensed matter theory

Prof. Titus Neupert

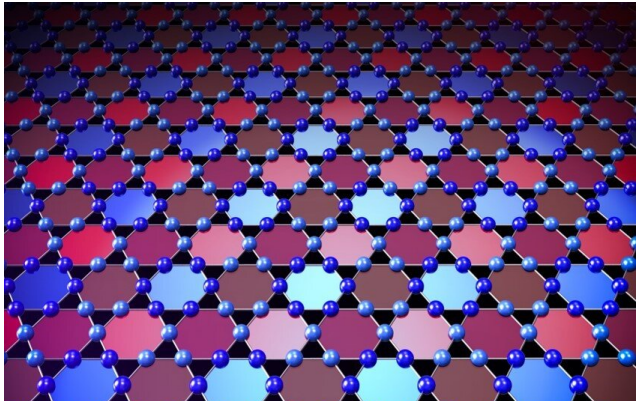
We study **topological phases of quantum matter** with numerical and analytical tools. Topological electronic states are characterized universal and robust phenomena, such as the Hall conductivity in the integer quantum Hall effect, that are of fundamental interest or promise applications in future electronics. We study and propose **concrete materials** to realize such topological effects, but are also interested in studying abstract models to understand what phases of matter can exist in principle.
Our numerical toolbox includes **neural network algorithms** to study strongly interacting quantum many-body systems. Furthermore, we work at the interface of **quantum computing** and condensed matter physics.

https://www.physik.uzh.ch/g/neupert

Superconductivity and charge order in kagome compounds

Condensed matter physics is to a large extent concerned with the classification and characterization of all possible phases that many electrons can form in a crystal. The richness of such phases and their interplay comes with ever new surprises. Yet, there are certain materials in which physicists expect more interesting phases than in others, simply from their crystal lattice structure. A long-studied example is the kagome lattice, formed by corner sharing-triangles. Electronic states on the kagome lattice are strongly frustrated, meaning that simply ordered classical states are degenerate and a quantum-mechanical superposition is favored.

In 2021 we studied in intense collaborations with experimental groups from Princeton University and the Paul Scherrer Institute a new class of kagome lattice materials that harbor types of electronic order which were likely never probed before. The three compounds AV_3Sb_5 (A=K, Rb, Cs) all show charge order when cooled to 70–90 K and, at much lower temperature, superconductivity. In a charge ordered phase, electrons spontaneously modulate their density, thereby breaking some symmetries of the system. The symmetry breaking we found in the kagome metals is remarkable for two



Kagome lattice with a modulation of 2×2 *unit cells originating from unconventional charge order.*

reasons: (i) not only do the electrons break lattice symmetries, but they also break time-reversal symmetry by forming small loop currents on the lattice scale that generate magnetic fluxes; (ii) in contrast to previously observed charge orders, the electron-hole pairs attain a nonvanishing relative angular momentum in this state. To appreciate the importance of the latter, one should contrast charge orders with superconductors, in which electrons from particle-particle pairs. For them, higher-angular momentum states (e.g., *d*-wave superconductors such as the cuprates) are common. In contrast, charge orders are commonly implicitly considered to be of *s*-wave type and the higher angular momentum we found is a noteworthy exception. It is enabled by the unique electronic structure of the kagome lattice and relies on a sublattice interference mechanism through which certain electron waves become insensitive to the usually dominating local Coulomb repulsion.

Our findings were flanked by a flurry of research activities on these kagome metals. Their combination of quantum correlations, lattice frustration, and topological properties make them a unique material class to understand the interplay of these phenomena. A question that is largely open at this point is the nature of their superconducting phase. We have contrasted several scenarios in a theoretical study, but further experimental work is needed to differentiate between them.

Highlighted Publications:

1. Analysis of Charge Order in the Kagome Metal AV_3Sb_5 (A=K, Rb, Cs), Denner, M.M., *et al.*, Phys. Rev. Lett. **127**, 217601 (2021)
2. Unconventional chiral charge order in kagome superconductor KV_3Sb_5, Jiang, Y.-X., *et al.*, Nature Materials 20, 1353–1357 (2021)
3. Charge order and superconductivity in kagome materials, Neupert, T. *et al.*, Nature Physics, `https://doi.org/10.1038/s41567-021-01404-y` (2021)

Superconductivity and Magnetism

Professor Johan Chang

We investigate **quantum matter phases emerging from strong electronic interactions**. High-temperature superconductivity, strange metals, density-wave instabilities and electronic driven metal-insulator transitions are studied by synchrotron and laboratory based experimental techniques. At international synchrotrons, we are carrying out angle-resolved photo-emission spectroscopy (ARPES) and resonant inelastic x-ray scattering (RIXS) to reveal electronic structures and properties of correlated electron systems. Quantum phase transitions tuned by magnetic field or hydrostatic pressure are furthermore explored by high-energy x-ray diffraction. Within our laboratory, similar themes are probed by electrical and thermo-electrical transport measurements. Our group also has technical initiatives to develop innovative and compact cryo-cooling methodology. Finally, we are involved in data science analysing x-ray scattering results using machine learning methodology.

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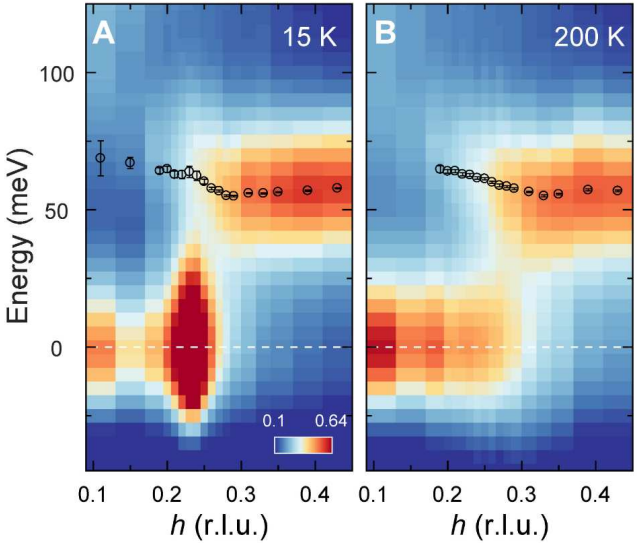
Charge order lock-in by electron-phonon coupling

Charge order is universal to all hole-doped cuprates. Yet, the driving interactions remain an unsolved problem. Electron-electron interaction is widely believed to be essential, whereas the role of electron-phonon interaction is unclear. Using ultrahigh-resolution resonant inelastic x-ray scattering (RIXS), we studied the in-plane bond-stretching phonon mode in stripe-ordered cuprate $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$. Phonon softening and lifetime shortening are found around the charge ordering wave vector, manifesting a significant electron-phonon coupling. In addition to these self-energy effects, the coupling strength is probed by its proportionality to the RIXS cross section. We find an enhancement of the electron-phonon coupling around the charge-stripe ordering wave vector at low temperature. Our study thus suggests that, in addition to electronic correlations, electron-phonon coupling contributes substantially to the emergence of long-range charge-stripe order in cuprates.



Temperature evolution of charge-stripe order and bond stretching phonon mode in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$ probed by RIXS.

Unconventional Transverse Transport

As exemplified by the growing interest in the quantum anomalous Hall effect, the research on topology as an organizing principle of quantum matter is greatly enriched from the interplay with magnetism. Combining electrical and thermoelectrical transport, we studied the magnetic Weyl semimetal $EuCd_2As_2$. Unconventional contribution to the anomalous Hall and anomalous Nernst effects were observed both above and below the magnetic transition temperature of $EuCd_2As_2$, indicating the existence of significant Berry curvature. $EuCd_2As_2$ represents a rare case in which this unconventional transverse transport emerges both above and below the magnetic transition temperature in the same material. The transport properties evolve with temperature and field in the antiferromagnetic phase in a different manner than in the paramagnetic phase, suggesting different mechanisms to their origin. Our results indicate $EuCd_2As_2$ is a fertile playground for investigating the interplay between magnetism and topology, and potentially a plethora of topologically nontrivial phases rooted in this interplay.

Highlighted Publications:

- Charge Order Lock-in by Electron-Phonon Coupling in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$
  Qisi Wang *et al.*, Science Advances **7**, 27 (2021)
- Unconventional Transverse Transport above and below the Magnetic Transition Temperature in Weyl Semimetal $EuCd_2As_2$
  Y. Xu *et al.*, Physical Review Letters **126**, 076602 (2021)
- Electronic reconstruction forming a C_2-symmetric Dirac semimetal in $Ca_3Ru_2O_7$
  M. Horio *et al.*, npj Quantum Materials **6**, 29 (2021)

Oxide Interface Physics

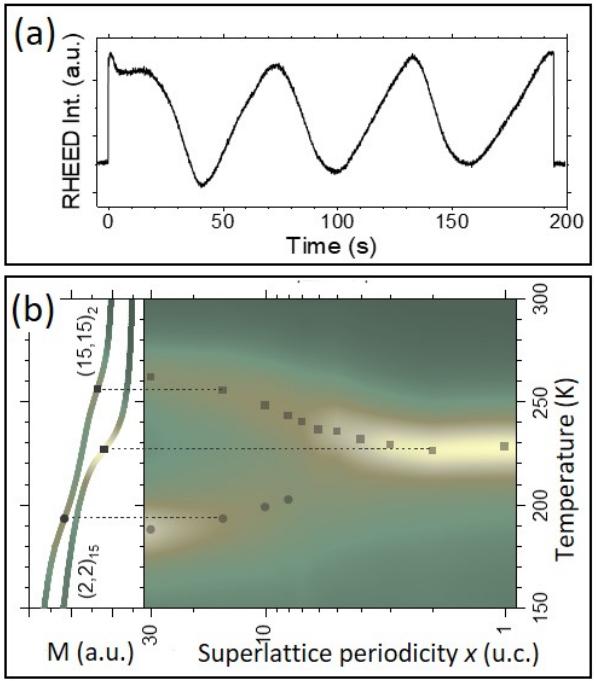
Prof. Marta Gibert

In our group, we grow transition metal oxide heterostructures (i.e. thin films, superlattices) and we investigate their functionalities. We especially focus on the study of the electronic and magnetic properties resulting from reduced dimensionalities and reconstructions occurring at oxide interfaces. Our goal is to understand the subtle atomic-scale structural and electronic mechanisms controlling interface physics in complex oxides. This knowledge is key for the rational design of materials with tailored properties. The atomic-scale precise oxide layers are grown by off-axis rf magnetron sputtering.

https://www.physik.uzh.ch/g/gibert

Transition metal oxides (TMOs) are an extensive class of compounds displaying a large variety of interesting physical properties (i.e. metal-insulator transitions, magnetism, superconductivity, etc.), which makes them highly attractive candidates for next-generation electronic devices. All these functionalities stem from strong electronic correlations and a complex interplay between the charge, orbital, spin and lattice degrees of freedom. Especially attractive are not just the bulk compounds, but also the ability to create artificial layered materials by stacking different oxide compounds one on top of the other, i.e. in the so-called thin films and superlattice structure configurations.

In order to track atomic layer growth in situ, we have assembled a new custom-built RF magnetron sputtering setup featuring Reflection High Energy Electron Diffraction (RHEED). The presence of magnets in magnetron sputtering hampers the use of RHEED in conventional sputtering designs. Therefore, a unique design with the two sputter guns facing each other in order to compensate the magnetic fields was here required. The vacuum components for this new system were constructed by the mechanical workshop of the department. The electronics workshop contributed to the control electronics. This advanced tool enables us to grow complex oxide thin films



(a) Intensity of the specular RHEED spot during the sputter growth of 3 unit cells of Nd_2NiMnO_6. (b) The left panel shows representative M(T) SQUID measurements for a $(2,2)_{15}$ and $(15,15)_2$ superlattice. The right panel shows the derivative dM/dT for all investigated periodicities x in a color scale. The discrete points indicate the magnetic transitions identified by local maxima in dM/dT.

with atomic precision through real-time monitoring of the intensity of the specular RHEED spot. Each oscillation corresponds to the growth of one unit cell (u.c.), Fig. (a).

Currently, we are focusing on the growth of the double perovskites La_2NiMnO_6 and Nd_2NiMnO_6 which exhibit the rare combination of insulating behavior and ferromagnetism with respective magnetic transitions at 280 K and 200 K. Using the atomic precision of our new setup, we grow superlattices of the two materials with a fixed total thickness of 60 u.c.. They feature stacks of x u.c. of La_2NiMnO_6 and Nd_2NiMnO_6, respectively, which is repeated y times; denoted as $(x,x)_y$. We investigate the interplay between the two ferromagnetic constituents by in-house SQUID magnetometry as function of superlattice periodicity, Fig. (c). Field cooling experiments reveal a single transition for superlattices with small periodicities, suggesting that it is energetically favorable for the system to avoid splitting up into ferro- and paramagnetic layers. On the other hand, for superlattices of large periodicity we clearly identify two transitions with an intermediary temperature range where only the La_2NiMnO_6 experiences ferromagnetism. We identify a minimum of $x = 8$ u.c. for the appearance of two separate para- to ferromagnetic transitions.

1. Ferromagnetic insulating epitaxially strained ...
G. De Luca *et al.*, APL Materials 9, 081111 (2021).

Low dimensional systems

Prof. Thomas Greber

We study objects like **zero dimensional endofullerene** molecules and **two dimensional (2D) boron nitride** layers in view of their functionality as nano-materials. Single molecule magnetism is the focus in the fullerene research, where we apply x-ray absorption and a sub-Kelvin superconducting quantum interference device. In the 2D materials activity we grow highest quality boron nitride on substrates up to the four inch wafer scale with chemical vapour deposition and subsequent exfoliation and device implementation. For these purposes we use a dedicated clean room, optical microscopy, ink jet printing and surface science tools such as low energy electron diffraction, photoemission and scanning tunnelling microscopy. At the Swiss Light Source we perform photoemission and x-ray absorption spectroscopy.

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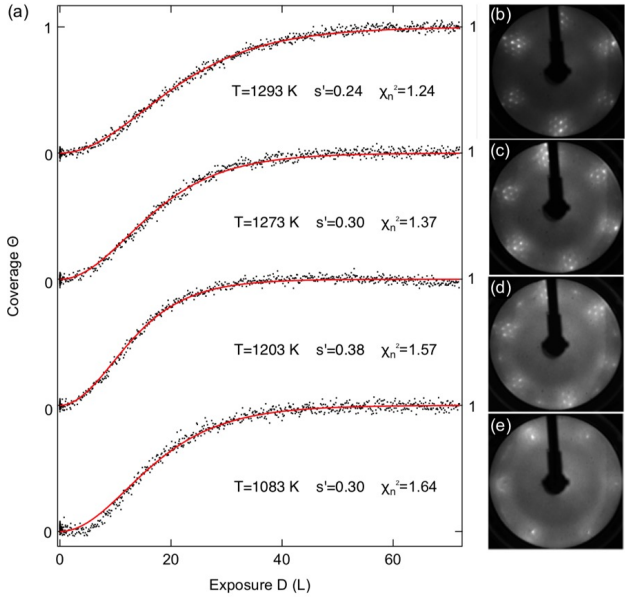
Wafer scale single layer *h*-BN on Pt(111)

Hexagonal boron nitride is considered as key material for the exploration and exploitation of two dimensional materials. Large scale single layer material may be grown by chemical vapour deposition of precursor molecules on hot transition metal surfaces like platinum. These surfaces act as catalysts for the decomposition of the precursors and their incorporation into the two-dimensional skin that forms. The growth process starts from *h*-BN nuclei and their merging into macroscopic sheets of material. The product is used as electrochemical electrode, template for supramolecular structures, as an ultimately thin membrane on a metal. The single layers can be exfoliated and transferred on arbitrary substrates. On insulators they may be used as single photon emitters. Furthermore, the *h*-BN/Pt(111) substrates serve as templates for the growth of insulating multilayer boron nitride with a low dielectric constant as it is needed for fast electronics and spintronics in next generation integrated circuits.



Growth kinetics and correlation to LEED patterns: (a) h-BN coverage on Pt(111) vs. borazine exposure. Black dots, data, red lines, tanh^2 fits with effective sticking parameters s'. A value χ_n^2 of 1 indicates a perfect fit of the model. (b-e) LEED patterns (Electron energy E=100 eV). (b) T=1293 K, (c) T=1273 K, (d) T=1203 K; note the minority phase 30 degrees away from the high symmetry direction, (e) T=1083 K growth temperature.

We optimised the growth of low-defect monolayer *h*-BN on 2 inch Pt(111)/sapphire wafers. The growth kinetics were monitored in situ with photoelectron yield measurements. They follow a tanh^2 law. The quality of *h*-BN/Pt(111) is studied with scanning low energy electron diffraction (LEED). The data indicate a strong dependence of the epitaxy on the growth temperature. [1].

The project is a collaboration with the Interuniversity Microelectronics Centre (IMEC) in Leuven where the Pt thin film substrates were produced. This activity is supported by the European Future and Emerging Technology flagship graphene.

Highlighted Publications:

1. Wafer-scale, epitaxial growth of single layer hexagonal boron nitride on Pt(111),
   A. Hemmi *et al.*, J. Phys. Mater. **4**, 044012 (2021)
2. Precise measurement of angles between two magnetic moments and their configurational stability in single-molecule magnets,
   R. Westerström *et al.*, Phys. Rev. B **104**, 224401 (2021)
3. Ferromagnetic insulating epitaxially strained La2NiMnO6 thin films grown by sputter deposition,
   G. De Luca *et al.*, APL Materials **9**, 081111 (2021)

Correlated Quantum Matter

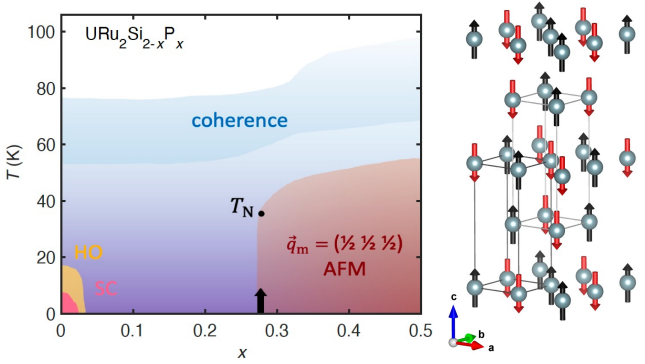
Prof. Marc Janoschek

Our research is centered on genuine quantum phenomena in bulk materials that arise due to collective electronic behavior. These electronic correlations strongly couple spin, charge and lattice degrees of freedom resulting in emergent and rich low-energy physics. We study materials in which such collective quantum phenomena at the atomic-scale are borne out in exotic and functional macroscopic properties. We tune the underlying quantum interactions via external control parameters (pressure, field, strain, crystal chemistry) to understand the properties of quantum materials. For this purpose, we probe quantum matter with state-of-the-art large-scale neutron, photon and muon experiments.
https://www.physik.uzh.ch/g/janoschek

Highlighted result

Strongly correlated electron materials are generally characterized by rich phase diagrams with energetically nearly-degenerate states that exhibit exotic physics. A formidable example is the heavy fermion material URu_2Si_2 for which a particularly abundant phase diagram has been revealed in the quest to understand the salient electronic properties of its unusual hidden order (HO) state. Here a large body of work has established that HO is markedly different from conventional spin or charge orders frequently found in strongly-correlated metals. Most notably, although the onset of the HO is marked by a second-order symmetry breaking phase transition visible in the heat capacity at T_0 = 17.5 K, the symmetry of its order parameter remains elusive.

In URu_2Si_2 strong electronic correlations arise due to the hybridization of localized uranium f electrons with the conduction electrons. In turn, unraveling the conundrum of HO requires a better understanding of the underlying duality of the itinerant and localized degrees of freedom. An impressive collection of studies has demonstrated that the HO state exists in close proximity to magnetic phases, which can be accessed by tuning via various control parameters including high magnetic fields, pressure and strain, as well as chemical substitu-



Phase diagram of $URu_2Si_{2-x}P_x$ (Left) featuring hidden order (HO), unconventional superconductivity (SC) and antiferromagnetic order (AFM) resolved by our neutron diffraction experiments (right).

tion, either on the uranium ruthenium site. The challenge in interpreting the consequences of doping f or d electrons is to disentangle the effects of varying the hybridization (e.g. by varying the degree of delocalization and spin-orbit coupling of the ligand), of the local environment (by variation of bond lengths and angles) and the variation of the Fermi surface.

A new substitution series is thought to address this issue, where it has been suggested from bulk measurements that (Si,P) weakens p–f hybridization, but affects the spacing and orientation of d-ligands only weakly. To test this microscopically, we carried out neutron diffraction to probe the order parameter of the new antiferromagnetic phase that is induced in $URu_2Si_{2-x}P_x$. This undertaking represents a major experimental challenge as the largest crystals of $URu_2Si_{2-x}P_x$ have a mass of only $\approx 0.5\,\mathrm{mg}$ and dimensions of $0.8 \times 0.8 \times 0.05\,\mathrm{mm}^3$. We overcome the issue by using the latest generation time-of-flight neutron diffractometer WISH, which combines high-brilliance neutron moderators with highly optimized focusing neutron guides to enable experiments on single crystals with dimensions of $\sim$ 1,mm and less. Our study reveals a simple c-axis colinear antiferromagnetic structure with localized magnetic moments (see Figure). Through comparisons with other tuning studies, we are able to delineate the mechanisms by which silicon-to-phosphorus substitution affects the system. In particular, both the localization of itinerant $5f$ electrons as well as the magnetic ground state appear to be a consequence of the increase in chemical potential. Further, enhanced exchange interactions are induced by chemical pressure and lead to magnetic order, in which an increase in inter-layer spacing may play a special role.

Highlighted Publications:

1. Collinear antiferromagnetic order in $URu_2Si_{2-x}P_x$ revealed by neutron diffraction
   M. C. Rahn *et al.*
   Phys. Rev. B 103, 214403 (2021)

Quantum Matter

Prof. Fabian Natterer

Our group investigates the properties of two-dimensional quantum materials. We explore how materials receive their properties from the interaction between individual atoms and molecules that we control with atomic precision. We furthermore study 2D van der Waal materials and develop new measurement protocols for advanced scanning probe microscopy investigations, such as electron spin resonance, pump-probe spectroscopy, and we combine parallel spectroscopy and compressed sensing for fast quasiparticle interference imaging.

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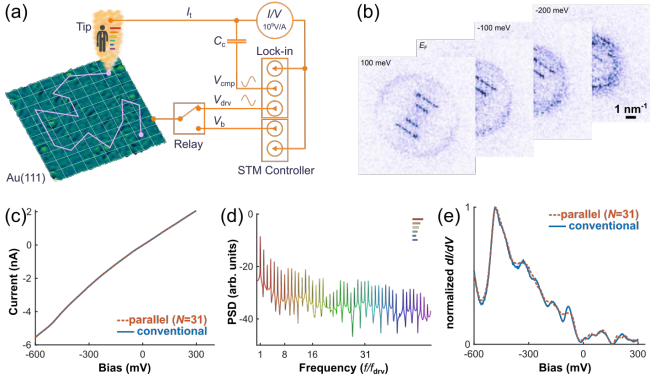
Fast Spectroscopic Mapping of two-Dimensional Quantum Materials

The band structure of two dimensional quantum materials can be inferred from SPM measurements with quasiparticle interference imaging. It works by measuring the point spectroscopy (local density of states) at every topographic location. To speed up this traditionally slow technique, we utilize compressed sensing and parallel spectroscopy. While the former enables the measurement of fewer locations, the latter speeds up the LDOS recording. In combination, we achieve three orders of magnitude faster mapping, which reduces a weeklong measurement to few minutes. Our fast mapping enables previously inconceivable measurement protocols, such as high momentum or energy resolution maps, or accessing the energy-dependent decay length. We plan to use our fast mapping schemes to explore the vast parameter space formed by temperature and uniaxial strain in the study of quantum materials near their critical points.

Scanning Probe Microscopy based ESR

Our second main project is the development of novel spin sensors for electron spin resonance (ESR) with a scanning probe microscope. Our goal is to embed a molecular qubit into the SPM tip and use it as a detector for magnetic sig-



Fast spectroscopic mapping of two dimensional quantum materials. Using the route of a traveling salesperson, we visit only a fraction of the usual measurement locations at which we measure the local density of states with a parallel spectroscopy technique. From the application of compressive sensing, we reconstruct the sparse information content in the Fourier domain, which is related to the band-structure of the material. Our 1000-fold faster mapping scheme enables previously cumbersome measurement protocols, such as the exploration of a large parameter space in the discovery of quantum materials.

natures at the atomic scale. We pursue two complementary routes of electrical and optical readout to achieve universal quantum sensing with atomic resolution as an alternative to nitrogen vacancy centers whose spatial resolution plateaus at 5 nm. Our sensor will illuminate the atomic-scale origin and properties of radicals, artificially built quantum matter, and noncolinear magnetic structures.

Highlighted Publications:

1. Sparse sampling for fast quasiparticle-interference mapping,
   J. Oppliger and F. D. Natterer,
   Physical Review Research **2**, 023117 (2020),
   https://doi.org/10.1103/PhysRevResearch.2.023117
2. Fast spectroscopic mapping of two-dimensional quantum materials,
   B. Zengin, J. Oppliger, D. Liu, L. Niggli, T. Kurosawa, F. D. Natterer,
   Physical Review Research 3, L042025 (2021),
   arXiv:2102.00054

Surface physics

Prof. Jürg Osterwalder

We study **model catalysts** based on single-crystalline oxide surfaces that are prepared under ultra-high vacuum conditions and characterize them in terms of structure, electronic structure, as well as photoexcited electron dynamics. Our laboratory is equipped with a toolbox of **surface science** methods and a laser system that can be used to investigate such phenomena at the **atomic and molecular level** and at the **femtosecond time scale**. Moreover, the group operates an endstation for **ambient-pressure XPS** at the Swiss Light Source at PSI, where catalysts can be studied under conditions close to the relevant pressure regime. Specific systems include a Cu_2O catalyst underneath a monolayer of hexagonal boron nitride for studying **catalysis in confined spaces**, stable **single-atom catalysts** on Fe_3O_4 that minimize the need for precious metals, and **carbon nanodots** on TiO_2 as an efficient photosensitizer for **solar water splitting**.

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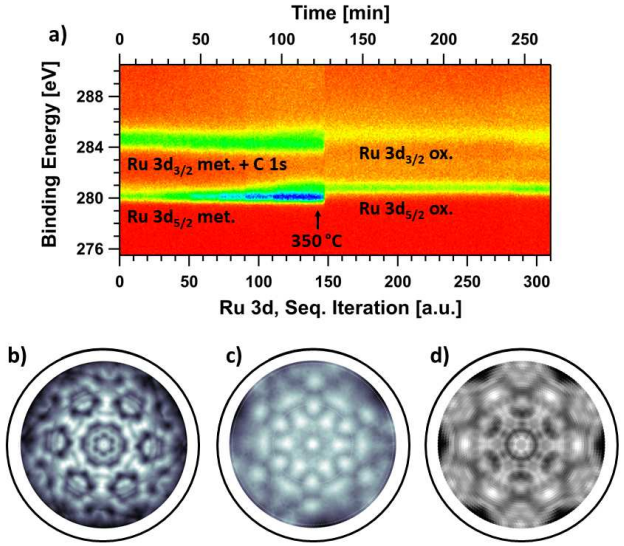
Real-time observation of the autocatalytic oxidation of ruthenium metal by near-ambient pressure XPS

Carbon monoxide is a toxic by-product of many combustion processes and needs to be removed from the exhaust gas via oxidation to CO_2. The rate limiting step in the CO oxidation reaction is the dissociation of O_2 molecules that requires a catalyst, typically a platinum group metal. Among these, ruthenium is the exception, as it is the oxide (RuO_2) that is a very efficient catalyst, far superior to Ru metal or other platinum group metals.

When Ru metal is exposed to a mixture of CO and air, a thin RuO_2 layer is formed at the surface, thus activating the catalyst. This process is autocatalytically enhanced: small RuO_2 nuclei that form during a sluggish induction phase promote oxygen dissociation that feeds and accelerates the oxide growth. We have studied this process with ambient pressure x-ray photoelectron spectroscopy (APXPS) at the ISS beamline of the Swiss Light Source, using a single crystalline Ru(0001) sample.



Autocatalytic oxidation of Ru(0001): (a) Evolution of Ru 3d XPS spectra as a function of time and temperature presented as a heat map (red/blue corresponding to minimum/maximum intensity). Up to iteration 140 the Ru(0001) sample was gradually heated to a temperature of 350° C, where it remained constant up to iteration 210. After a subsequent increase to 400° C, it was cooled down to room temperature. (b) XPD pattern of the Ru 3d core level from the clean Ru(0001) surface. (c) Same, after the oxidation reaction. In (d) the multiple scattering simulation of the latter is shown, using a model cluster representing three domains of RuO_2(110), each rotated by 120° with respect to the other.

Panel (a) shows the evolution of the Ru 3d core level spectrum as a function of time while the Ru(0001) sample is gradually heated under an oxygen partial pressure of 1×10^{-2} mbar. After a 6-minute induction time at a constant temperature of 350°C, the binding energies switch within one single iteration (42 s) to a fully oxidized spectrum. The spectra measured during the induction period support the existence of an O-Ru-O trilayer structure at the surface as an intermediate phase before rapid oxide formation. The latter consists of three rotated domains of RuO_2 with (110) orientation, as evidenced by x-ray photoelectron diffraction (XPD) patterns (panels (b)-(d)).

Highlighted Publications:

1. Thermal oxidation of Ru(0001) to RuO_2(110) studied with ambient pressure x-ray photoelectron spectroscopy, J. T. Diulus *et al.*, J. Phys. D: Appl. Phys. **54**, 244001 (2021)
2. Factors influencing surface carbon contamination in ambient pressure x-ray photoelectron spectroscopy, N. Comini *et al.*, J. Vac. Sci. Technol. A **39**, 043203 (2021)
3. Charge carrier dynamics and self-trapping on Sb_2S_3(100), L. Grad *et al.*, Phys. Rev. Materials **5**, 075401 (2021)

Phase Transitions, Materials and Applications

Prof. Andreas Schilling

We are interested in selected topics in materials research, spanning the entire spectrum from **searching new materials**, their **characterization**, and corresponding **applications**. We have been particularly active in **superconductivity, magnetism and thermodynamics**. Our laboratory is equipped with modern furnaces for material synthesis, various ^{4}He/^{3}He cryostats and a dilution cryostat, all with superconducting magnets.

We are structuring thin superconducting films at the FIRST Center for Micro- and Nanoscience at ETHZ and are using them both for basic research and applications. While the physics of thin-film superconductors is a fascinating research topic by itself, corresponding nanostructures may serve as ultrafast single-photon detectors in the infrared, visible and X-ray range.

https://www.physik.uzh.ch/g/schilling

Size dependent transition to superconductivity and superconductor-to-insulator transition in narrow micro-bridges

We have investigated a series of superconducting bridges based on homogeneous amorphous WSi and MoSi films, with bridge widths w ranging from 2μm to 1000 μm and film thicknesses d from 4-6 nm and 100 nm. Upon decreasing the bridge widths below the respective Pearl lengths $\Lambda = 2\lambda^2/d$, which can be substantially larger than the London penetration depth λ, we observe in all cases distinct changes in the characteristics of the resistivity in an external magnetic field B. Near the critical temperature T_c, the resistivity curves $R(B,T)$ separate for each of the films at a well-defined and field-dependent temperature, resulting in a dramatic suppression of the resistivity and a sharpening of the transitions with decreasing bridge width w (Fig. 1). As the interaction between vortices can change from long-range to an exponentially weak and short-range interaction as soon as the characteristic length scale of the su-

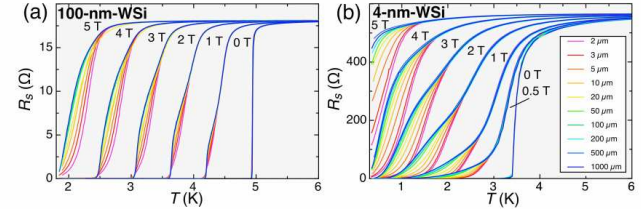


Fig. 1: Sheet resistance $R_s(B,T)$ for micro-bridges of amorphous WSi.

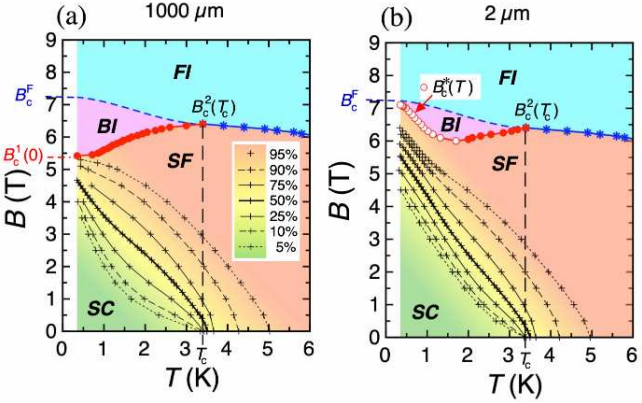


Fig. 2: The sequential superconductor (SC)-Bose insulator (BI)-Fermi insulator (FI) quantum-phase transitions for very wide (a) and narrow (b) 4 nm thin WSi bridges.

perconducting system is smaller than Λ, the vortices most likely become prone to pinning in the narrow bridges, which explains the decrease in resistance near T_c. In the low-temperature limit, the corresponding resistivity curves and magnetic phase diagrams dramatically change as well (Fig. 2 and movies on weblinks 1 and 2 for 4 nm thin WSi). In very wide films (Fig. 2 a), a sequential superconductor-to-Bose insulator-to-Fermi insulator quantum-phase transition takes place. By limiting their size w smaller than Λ, however, the superconducting state recovers and re-enters the originally Bose-insulating state as a consequence of the increased disorder (Fig. 2b). As a consequence, one observes a direct superconductor-to-Fermi insulator transition. In the narrow films, the critical exponent products associated with the phase transitions diverge along the corresponding phase boundaries with increasing magnetic field, which is a hallmark of a quantum-Griffiths singularity.

Highlighted Publications:

1. Size dependent nature of the magnetic-field ..., X. Zhang et al., Communications Physics 4, 100 (2021)
2. Physical properties of amorphous MoSi films ..., X. Zhang et al., Supercond. Sci. Technol. 34, 095003 (2021)

Coherent Diffraction Imaging

PD. Tatiana Latychevskaia (Paul Scherrer Institut)

Coherent diffraction imaging (CDI) and holography are lens-less imaging techniques where the intensity of the wave diffracted by the sample is acquired by a detector in the far field. The phase distribution of the diffracted wave together with the sample structure is then reconstructed by applying numerical methods. Using short wavelength radiation, such as electron or X-ray waves, allows imaging at atomic resolution. We are developing lens-less imaging methods towards high-resolution and three-dimensional imaging of nano-scaled objects, two-dimensional materials (graphene, TMDs, etc) and macromolecules.

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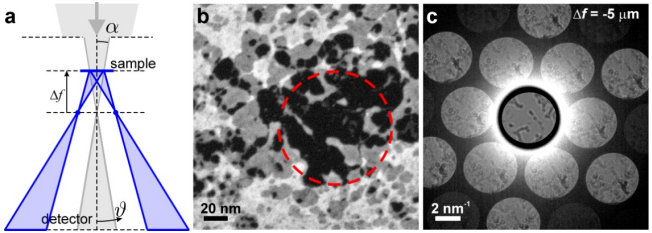
Our current activities include:

1. Experimental convergent beam electron diffraction of two-dimensional materials (graphene, boron nitride, transition metal dichalcogenide (TMD) materials, etc) and nano-scaled objects such as individual macromolecules [1];

2. Light optical experiments for design and testing novel imaging techniques (holography, coherent diffraction imaging, ptychography, quantum optics imaging techniques, etc);

3. Theoretical and numerical study of wave-matter interaction at atomic scale: effects of wave coherence, multiple scattering, etc. Simulations of electron and X-ray wave scattering and wave propagation in various materials;

4. Developing algorithms for high-resolution (atomic-resolution) and three-dimensional reconstruction of



Convergent beam electron diffraction (CBED) of graphene with adsorbates: (a) experimental scheme, (b) high-angle annular dark field image of the sample, and (c) CBED pattern [1].

samples' structures from their diffraction patterns using iterative phase retrieval, machine learning etc [2, 3].

1. Holographic convergent electron beam diffraction (CBED) imaging of two-dimensional crystals, T. Latychevskaia, S. Haigh and K. Novoselov, Surf. Rev. Lett. **28**(8), 2140001 (2021)
2. Three-dimensional structure from single two-dimensional diffraction intensity measurement, T. Latychevskaia, Phys. Rev. Lett. 127 (6), 063601 (2021) doi:10.1103/PhysRevLett.127.063601
3. Phase retrieval methods applied to coherent imaging, T. Latychevskaia, Advances in Imaging and Electron Physics 218 1 62 (2021) doi:10.1016/bs.aiep.2021.04.001