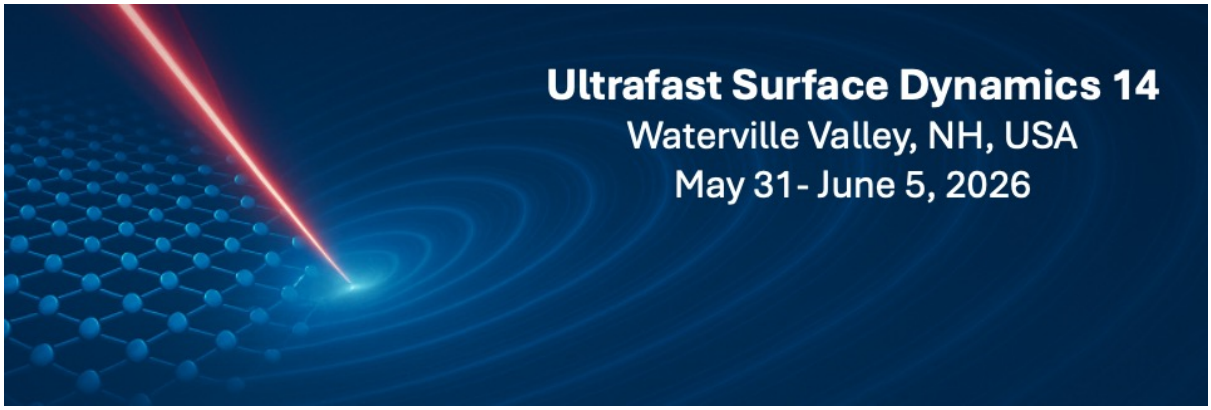

USD14 Oral Presentation Abstracts

In order of appearance

Optics and dynamics of excitons and trions in 2D materials

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Monolayer transition metal dichalcogenides (TMDs) and related van der Waals heterostructures exhibit a rich exciton and trion landscape including bright and a variety of dark states as well as spatially separated interlayer and layer-hybridized exciton and trion states. Based on a density matrix formalism, we perform microscopic modeling of many-particle physics determining exciton and trion optics, dynamics and transport phenomena in these technologically promising materials.

In joint theory-experiment studies, we reveal that phonon-mediated scattering via hybridized dark excitons governs the ultrafast charge transfer process in TMD heterostructures [1]. We study the phonon-driven relaxation cascade of hot interlayer excitons after the charge transfer has occurred and track the exciton relaxation pathway across different moiré mini-bands and identify the key phonon scattering channels [2]. We unravel a phonon bottleneck in the flat band structure at low twist angles and at low temperatures preventing excitons to fully thermalize into the lowest state explaining the previuosly measured enhanced emission intensity and lifetimes of excited moiré exciton states. We show that counterintuitively flat bands, which typically trap excitons, can significantly enhance exciton propagation due to the emergence of hot excitons [3]. Furthermore, we determine the trion energy landscape in TMDs including bright and dark states and reveal that a mass imbalance between equal charges within a trion results in much smaller trion binding energies. We predict unambiguous trion signatures in photoluminescence and ARPES spectra [4,5] and investigate the ultrafast exciton-to-trion conversion by applying short pulses in the terahertz spectral range [6].

The gained microscopic insights are crucial for understanding and controlling many-particle phenomena governing exciton optics, dynamics and transport in technologically promising 2D materials and related heterostructures.

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Have you seen a PHz clock in your mirror this morning?

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Interferometric time-resolved multiphoton photoemission (mPP) experiments record the nonlinear coherent responses of solids. mPP spectra can be understood as a Floquet engineering process in which electrons are lifted above the vacuum energy level to undergo photoemission and spectroscopic analysis of their energy and momentum [1]. The primary response to light is electron-hole polarization, which can be real or virtual [2]. In metals, this outcome elicits a screening response that typically appears on a sub-femtosecond time scale, as governed by the metal's electronic response function, and exemplified by the plasmon frequency [3]. This can generate an internal field that modulates the electronic response, as described by the Mathieu function. I will describe how Floquet engineering and the Matheu response define a clock operation with PHz-level frequency rigidity and attosecond reproducibility under ambient nonlinear-optical conditions. You will never look into a mirror the same way again.

References: [1] M. Reutzel, A. Li, and H. Petek, Phys. Rev. X 9, 011044 (2019). [2] X. Cui, C. Wang, A. Argondizzo, S. Garrett-Roe, B. Gumhalter, and H. Petek, Nat Phys 10, 505 (2014). [3] V. M. Silkin, P. Lazić, N. Došlić, H. Petek, and B. Gumhalter, Phys. Rev. B 92, 155405 (2015).

Tracking exciton wavefunctions to unravel energy and charge transfer in 2D-organic and moiré materials

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Two-dimensional quantum materials and organic semiconductors promise transformative optoelectronics through efficient charge and energy transfer at hybrid interfaces, where excitons mediate light-matter interactions on ultrafast timescales and nanometer lengthscales. Using table-top femtosecond photoemission orbital tomography (POT) via time-resolved momentum microscopy, we can track exciton dynamics across organic-inorganic interfaces and in moiré heterostructures [1-5]. Here, we recently have realized three-dimensional photoemission orbital tomography (3D-POT) [1] and have extended the method to exciton photoemission tomography (ex-POT) [2,3], revealing multiorbital contributions, localization, and charge-transfer character in diverse systems [4,5]. At a 2D-organic WSe2-PTCDA semiconductor interface, we observe the emergence of hybrid excitons, where the wave function is a coherent combination of Frenkel-like and Wannier-like components with mixed intra- and interlayer nature [2]. In this hybrid system, energy transfer is established on sub-100-fs timescales via dipole-dipole (Förster-type) coupling across the interface. Capturing the spatial evolution and energy dissipation processes of excitons directly in momentum-energy space is a versatile method to visualize exciton-driven transfer processes in real time across varied interfaces, enabling flexible exploration and tailored optoelectronic functionality.

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Quantum Dynamics of Charge Carriers in Optoelectronic Materials and Interfaces

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Excited state dynamics play key roles in condensed phase, nanoscale and molecular materials designed for optoelectronic applications and energy conversion. Controlling these far-from-equilibrium processes and steering them in desired directions require understanding of material's dynamical response on the nanometer scale and with fine time resolution. We couple real-time time-dependent density functional theory for the evolution of electrons with non-adiabatic molecular dynamics for atomic motions to model such non-equilibrium response in the time-domain and at the atomistic level, with both ab initio and machine learning tools. The talk will introduce the simulation methodology and discuss several exciting applications, including metal halide perovskites, 2D materials, semiconducting and metallic nanocrystals, photo-induced structural, electric and phase transitions, exciton-polaritons, and their assemblies. Modeling and understanding photo-induced charge and energy transfer, plasmonic excitations, Auger-type processes, structural and spin evolutions, and energy relaxation create many challenges due to a broad range of size, energy and time-scales, and qualitative differences between periodic and molecular, and inorganic and organic matter. Our simulations provide a comprehensive and unifying description of quantum dynamics on nanoscale, characterize the timescales and branching ratios of competing processes, resolve debated issues, and generate theoretical guidelines for development of novel systems.

Time-resolved photoemission orbital tomography of molecular excitations at surfaces

Marcel Theilen, Siegfried Kaidisch, Monja Stettner, Sarah Zajusch, Eric Fackelman, Alexa Adamkiewicz, Robert Wallauer, Andreas Windischbacher, Christian S. Kern, Michael G. Ramsey, François C. Bocquet, Serguei Soubatch, F. Stefan Tautz, Peter Puschnig and Ulrich Höfer

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Photoemission orbital tomography (POT) is a powerful technique, by which the electron distribution of orbitals of well-ordered molecules at solid surfaces can be imaged in momentum space [1]. Recently, we combined the method with laser pump-probe techniques to investigate the dynamics of charge transfer processes at molecular interfaces [2,3]. In this talk I will discuss how time-resolved POT (tr-POT) can image the momentum-space distribution and temporal evolution of molecular excitons [4]. These bound states of electrons and holes govern light-matter interactions in organic semiconductors, yet their full quantum mechanical wavefunctions have remained experimentally elusive.

For the model system α-sexithiophene (6T) on a Cu(110)-p(2x1)O surface, we determine a spatial extent of 9 Åfor the exciton. It is seen to span about three neighboring molecules with a distinct phase modulation. From the temporal evolution of the recorded photoemission momentum maps, we derive a reduction of size of the exciton by about 20% during its 420-fs lifetime, which we attribute to self-trapping [4]. Our results resolve a long-standing debate on the exciton character in organic semiconductors and establish tr-POT as a general method to experimentally access exciton wavefunctions with spatial, phase and time resolution.

Time-Resolved Photoemission Electron Microscopy of Two-Dimensional Materials

Zhi-Heng Loh

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The application of two-dimensional transition metal dichalcogenides (TMDs) to optoelectronics requires a detailed understanding of their elementary carrier dynamics. In this talk, I will present some results obtained from our investigations of TMDs using femtosecond time-resolved photoemission electron microscopy (TR-PEEM). In 1L-WSe_2, TR-PEEM imaging reveals two distinct relaxation timescales following 2.41-eV excitation and 3.61-eV probing: a rapid 0.1-ps component assigned to intervalley electron scattering, and a longer picosecond decay attributed to exciton–exciton annihilation [1]. Spatial mapping uncovers heterogeneous lifetimes within a single flake [2], with shorter lifetimes at edges, emphasizing the impact of disorder on carrier dynamics. At the 1L-MoS_2/Au TMD-metal interface, we resolve hot-electron transfer rates as a function of local interfacial distance [3]. These rates decay exponentially with a surprisingly small attenuation coefficient of $\beta \quad 0.06 \pm 0.01$ Å^{-1}. Ab initio simulations suggest this weak distance dependence arises from surface plasmon-like states that mediate charge transfer, making the process robust against structural variations. Finally, we examine strain-induced effects on sub-picosecond dynamics in wrinkled multilayer MoS_2 [4]. TR-PEEM and nonadiabatic ab initio molecular dynamics reveal faster Γ-valley electronic relaxation in wrinkled regions due to enhanced nonadiabatic coupling driven by increased vibrational amplitudes and density of states. Together, these studies highlight the need for spatially resolved ultrafast techniques to unravel the complex interplay of structure and dynamics in TMDs, and suggest routes for tuning performance via strain and interfacial engineering.

References: [1] L. Wang et al., Nano Lett. 18, 5172 (2018) [2] N. T. W. Koo et al., J. Chem. Phys. 161, 174201 (2024) [3] C. Xu et al., ACS Nano 15, 819 (2021) [4] C. Xu et al., ACS Nano 17, 16682 (2023)

Ultrafast Plasmon Polariton Dynamics of $MoOCl_2$

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Controlling light propagation at the nanoscale with low loss and directional selectivity is a key goal for next-generation photonic technologies. Hyperbolic van der Waals materials offer a compelling route toward this goal, as their anisotropic permittivity tensors can give rise to a rich landscape of guided electromagnetic modes. In this talk, I will present our recent work using time-resolved photoemission electron microscopy (TR-PEEM) to directly image and characterize plasmon polariton dynamics in molybdenum oxydichloride ($MoOCl_2$) with nanometer spatial and sub-femtosecond temporal precision [1]. Our experiments reveal a previously unidentified long-range anisotropic plasmon polariton (LRAPP) mode that arises from the coupling of interfacial excitations in thin $MoOCl_2$ flakes. This mode propagates directionally along the metallic crystal axis over distances exceeding 10 μm, roughly three times farther than the previously studied hyperbolic mode, while exhibiting intrinsically lower optical losses. By tracking the real-space, real-time evolution of LRAPP wavepackets, we extract both phase and group velocities at the nanoscale and directly observe polariton reflections at crystal edges. These edge interactions, including round-trip propagation across the flake, demonstrate the potential of $MoOCl_2$ as a platform where both deeply confined and long-range directional modes coexist within a single natural material operating at visible wavelengths. I will discuss the implications of these findings for on-chip nanophotonic routing and the broader opportunities that spatiotemporal polariton imaging offers for understanding collective excitations in anisotropic quantum materials.

References: [1] Atreyie Ghosh, Calvin Raab, et al. Nat. Commun. In Press. (2026)

THz-induced Metastability and Ultrafast Dynamics of Local Charge Order in TaS_2 probed by THz-STM

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Controlling materials with ultrashort light pulses can open up new pathways to novel electronic and structural states. Understanding how spatial inhomogeneity at the atomic scale affects these dynamics requires simultaneous femtosecond temporal and angstrom spatial resolution. Here, we use THz scanning tunneling microscopy to study the local emergence and ultrafast dynamics of THz-light-induced metastable states at the surface of the prototype layered quantum material 1T-TaS_2. Pulsed THz excitation can drive long-lived, quasi-stationary changes in the local electronic structure that are localized near defects and domain boundaries and are attributed to local changes in the out-of-plane stacking of Star-of-David clusters. At the same time, THz-lightwave-driven tunneling reveals the femtosecond dynamics of the local charge order, including 2.5 THz oscillations of the charge density wave amplitude mode and a previously unobserved 1.3 THz mode attributed to interlayer shear vibrations. Our results demonstrate how atomic-scale inhomogeneities can actively mediate access to light-induced phases in correlated materials and pave the way for the atomic-scale control and spectroscopy of nonequilibrium and metastable quantum states.

Condensed Matter Research at the LCLS via Ultrafast X-ray Scattering

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The use of ultrashort X-ray pulses offers new opportunities to study fundamental interactions in materials exhibiting unconventional quantum states, particularly in quantum materials where charge density waves, light-induced phases and high-temperature superconductivity populate novel unconventional phase diagrams. To understand the microscopic interdependence between the competing degrees of freedom, such as electrons, lattice and spin, a probe capable of discerning interactions and excitations on their natural length, energy and time scales is necessary. In this talk, I will present capabilities at the LCLS to tackle this physics with ultrafast x-ray scattering techniques – particularly resonant inelastic x-ray scattering (RIXS) – on solid state samples. I will present capabilities at the newly commissioned qRIXS endstation, as well as from a wide range of instruments at the LCLS. Available ultrafast laser excitations include coherent and tunable ultrashort pulses controlled in time and wavelength and extending from the THz to the UV ranges, thus providing the ideal platform to pursue novel light-induced states. In terms of results, I will focus on recent RIXS experiments at the qRIXS endstation using the novel high repetition rate x-ray source capable of reaching a 33 kHz beam rate. Finally, I will review and discuss upcoming development plans for condensed matter research at the LCLS.

NSF NeXUS capabilities for ultrafast surface studies

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NSF NeXUS is an open-access user facility that enables observation of electron motion with sub-femtosecond time resolution, angstrom spatial resolution, and element-specific spectral resolution. NeXUS provides users with access to high-repetition rate, femtosecond pulses from the infrared to extreme ultraviolet for time-resolved measurements. NeXUS is supporting user measurements of surface states and surface dynamics using scanning tunneling microscopy and electron momentum microscopy. This talk will discuss the existing NeXUS capabilities, plans for advancements over the next few years, and how researchers can engage with NeXUS as users and partners.

UK Artemis: Pump-probe photoemission spectroscopy with small spot size and access to the full 3D Brillouin zone

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2) School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, UK

A complete picture of a material's electronic properties requires an understanding of its electronic dispersion in all three dimensions and of the spatial dependence of that dispersion. In angle-resolved photoemission spectroscopy (ARPES), accessing the full three-dimensional (3D) Brillouin zone requires scanning the probe photon energy. This has long been possible in static-ARPES measurements at synchrotrons. However, for pump-probe ARPES, it has only recently become feasible—first at free-electron lasers [1], and now across a more limited energy range accessible via high-harmonic generation (HHG) [2,3] at tabletop laser beamlines. UK Artemis is user facility of this second type, offering investigation of electron dynamics and complex light-matter interactions in optically pumped 3D systems [2], with real-space mapping down to length scales of a few-10s-of-μm. We are presently in the process of upgrading to a new commercial endstation, where measurement will be possible via hemispherical analyser (SPECS Astraios), FeSuMa Fermi surface mapper, and time-of-flight momentum microscope (SPECS Metis). Commissioning of the new endstation is planned for the second half of 2026.

References: [1] D. Kutnyakhov, et al., Rev. Sci. Instrum. 91, 013109 (2020) [2] P. Majchrzak, et al., Rev. Sci. Instrum. 95, 063001 (2024) [3] M. Heber, et al., Rev. Sci. Instrum. 93, 083905 (2022)

Investigation of Quantum Materials at FEL

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Understanding how quantum materials evolve far from equilibrium is a central challenge in condensed matter physics. Many of their most intriguing properties like collective ordering phenomena, emergent quasiparticles, and intertwined electronic, magnetic, and structural phases, arise from subtle couplings between charge, spin, orbital, and lattice degrees of freedom. Probing these dynamics on their intrinsic femtosecond and nanometer scales is essential for uncovering the microscopic mechanisms that govern functionality and for identifying routes toward controlling material properties on demand.

Recent advances in ultrafast light sources have dramatically expanded our ability to access nonequilibrium states. High-repetition-rate free-electron lasers such as FLASH enable experiments that combine element specificity, orbital sensitivity, and extended momentum reach, bridging local chemical information with band-structure and structural dynamics.

The recent upgrade to seeded soft x-ray operation at FLASH1 represents a transformative step, delivering unprecedented temporal coherence, superior spectral stability, high photon flux, and full polarization control. Looking ahead, the planned implementation of an undulator-based THz source will add a fully synchronized pump capability, enabling selective excitation of low-energy collective modes and correlated phases. Together with seeded soft x-ray probing, this will create a uniquely powerful platform for real-time control of quantum materials.

Tracking Collective Dynamics at interface and surfaces by x-ray and THz techniques

Haidan Wen

Materials Science Division and X-ray Science Division, Argonne National Laboratory

Collective excitations at interfaces and surfaces govern functionality in quantum materials and nanoscale heterostructures, yet their dynamics often unfold on ultrafast timescales and nanometer length scales that are difficult to access simultaneously. This talk presents recent advances in ultrafast techniques, including x-ray scattering and THz spectroscopy, that enable the detection of collective dynamics at surfaces and interfaces on ultrafast timescales. In the first example, ultrafast x-ray diffraction reveals anisotropic structural dynamics in monolayer crystals [1] and collective dynamics of polar vortices and skyrmions in $PbTiO_3/SrTiO_3$ superlattices [2,3]. In the second example, a surface-sensitive spintronic terahertz emission spectroscopy is developed to characterize distinct surface phonon dynamics in $SrTiO_3$ and $KTaO_3$ that diverge significantly from their bulk counterparts [4]. An outlook on studying ultrafast surface dynamics at large-scale facilities will also be discussed.

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Second order nonlinear responses in even-layer CrSBr

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We present second harmonic generation (SHG) and photocurrent measurements on even-layer CrSBr under externally applied magnetic fields. Even-layer CrSBr exhibits PT-symmetric layered antiferromagnetic order below the critical temperature of approximately 140 K. Our SHG experiments reveal a pronounced transverse magnetoelectric effect: applying an out-of-plane magnetic field along the c-axis induces an in-plane electric polarization along the b-axis. Additionally, our photocurrent measurements demonstrate a significant circular photogalvanic effect when an in-plane magnetic field is applied along the a-axis.

These results highlight the strong tunability of the PT-symmetric antiferromagnetic order in even-layer CrSBr, and, more importantly, showcase the versatile magnetoelectric and nonlinear magneto-optical responses that emerge from this system.

Terahertz spectroscopy of a zero-field Wigner crystal

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Physics department, UC Berkeley and MSD, LBNL

In this talk I will discuss on-chip terahertz (THz) spectroscopy of Wigner crystal states in electrostatically gated monolayer MoSe2. We observe a sub-THz resonance corresponding to the pinning mode of a zero-field Wigner crystal, whose frequency is orders of magnitude higher than those under high magnetic fields. With increasing density towards melting, we find that the pinning mode of the Wigner crystal coexists with a growing Drude component characteristic of an electron liquid, and the competition between these two components in the conductivity spectra leads to the insulator-metal transition of the 2D electron system.

Polariton Chern Bands in 2D Material-Photonic Crystals

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Quantum geometry has emerged as a new framework for transport and nonlinear phenomena in novel states of matter. Photonic crystals are facile for realizing spatial geometry and symmetries by design. They have provided a fertile ground for exploring non-trivial quantum geometries where time reversal symmetry is preserved. But achieving Chern bands in photonic systems remains challenging due to the requirement of breaking time-reversal symmetry. Integration of 2D material excitons with photonic crystals allows control of the time-reversal symmetry via the excitonic medium, though opening a sufficiently large topological gap remains challenge in experiments in the conventional paradigm.

We show different pathways to realize Chern insulators in 2D material-photonic crystal systems based on the system's unique properties, where topological gap is opened at the center of the engineered Brillouin zone, readily allowing higher-order Chern bands and topological gap sizes two orders of magnitude larger than previously possible. We will also discuss experimental implementations of such systems where large topological gaps and distributions of quantum geometry can be controlled electrically.

New Spin Functionalities on ultrafast Timescale in d-wave Altermagnets

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The concept of altermagnetism arose from the insight that specific combinations of real space rotations and spin space symmetries can produce compensated magnetic materials whose electronic structures break time reversal symmetry in an unconventional way [1]. This symmetry breaking yields alternating spin polarized bands in momentum space that assume d-, g-, or i-wave character [2]. Consequently, altermagnets possess a collinear magnetic order with zero net magnetization while displaying band dispersions that differ fundamentally from those of traditional ferromagnets and antiferromagnets. Beyond the emergence of novel current driven transport phenomena, the atypical time reversal violation permits a spin response to linearly polarized light in the optical regime.

The present work concentrates on the all-optical generation of spin polarization in d-wave altermagnets. By performing magneto-optical measurements on RuO_2 thin films only a few nanometers thick, we establish a direct correlation between the polarization state of an ultrashort pump pulse and both the sign and magnitude of a long-lived, optically induced electronic spin polarization [3]. These findings demonstrate that ultrafast optical pulses can excite and manipulate spin polarization in altermagnets. Importantly, the ability to create a spin imbalance with linearly polarized light in a fully compensated system is a distinctive consequence of the underlying altermagnetic symmetry [4].

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Subcycle momentum microscopy of Landau-Zener-Majorana transitions in lightwave-driven graphene

Vincent Eggers, Giacomo Inzani, Manuel Meierhofer, Lasse Münster, Jakob Helml, Robert Wallauer, Sarah Zajusch, Suguru Ito, Leon Machtl, Hao Yin, Christian Kumpf, François C. Bocquet, Changhua Bao, Jens Güdde, F. Stefan Tautz, Rupert Huber, and Ulrich Höfer

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Strong light fields have unlocked possibilities to control electron trajectories, engineer band structures and shape emergent phases of matter [1,2]. Understanding the underlying mechanisms crucially requires the visualisation of lightwave-driven electron motion directly in the band structure. While photoelectron momentum microscopy can image optically excited electrons, actual subcycle videography has been restricted to the centre of the Brillouin zone and was limited to a small class of materials [3,4]. Here, we introduce attosecond-precision, subcycle band-structure videography covering the entire first Brillouin zone. The new platform combines the best of both, momentum microscopy and subcycle ARPES. It increases the momentum area accessible of subcycle photoemission by more than two orders of magnitude and the available field strengths by one order of magnitude.

The power of the new experiment is demonstrated with an investigation of Landau-Zener-Majorana (LZM) transitions in graphene. Non-adiabatic LZM tunnelling is believed to govern field-driven interband dynamics in solids but has remained notoriously elusive despite its fundamental importance. Our new approach clearly reveals the periodic interplay of field-driven interband LZM tunnelling and intraband acceleration of quasi-relativistic fermions along the Dirac cone directly in full 2D momentum space. The extremely non-thermal electron distributions also allow us to disentangle competing scattering processes and assess their impact on coherent electronic control through electron redistribution and thermalization.

Following the same principle, we expect our subcycle band-structure videography to resolve a plethora of other key questions ranging from optical engineering of novel band structures and phase transitions to light field-driven sculpting of molecular orbitals.

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Subcycle videography of strong-field controlled electrons at surfaces

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2) Department of Physics, Philipps-University of Marburg, Germany

Lightwave electronics has revolutionized our way of controlling electronic quantum motion. The idea is to utilize the carrier field of light as an alternating voltage to accelerate electrons. On time scales faster than an optical cycle, electrons can move through solids without scattering, unleashing an all-coherent quantum world full of promise for future quantum technologies [1]. Subcycle dynamics, such as Bloch oscillations [2], electron-hole recollisions [3], topological trajectories [4], and spin-polarized Dirac currents [5] manifest in hallmark optical signatures, such as high-harmonic and high-order sideband generation. Angle-resolved photoelectron spectroscopy with subcycle resolution can even visualize lightwave-driven electron dynamics in direct band-structure videography, resolving ballistic motion of Dirac currents and Floquet-Bloch band-structure engineering [6]. By combining this idea with photoelectron momentum microscopy and XUV probe pulses, we recently expanded band-structure videography to cover the entire two-dimensional Brillouin zone. This breakthrough will allow us to directly image subcycle electron dynamics in momentum space in essentially all quantum materials. Lightwave electronics can also be pursued with real-space resolution. Lightwave-driven scanning tunnelling microscopes can videotape single molecules [7] and atomic defects [8] and observe the subcycle quantum flow of electrons [9]. By replacing the customary terahertz fields biasing the STM junction with phase-controlled single-cycle near-infrared light pulses, we combine attosecond temporal with atomic spatial resolution by taking snapshot images of a single adatom on a silver surface [10]. Our results offer a radically new way of watching and controlling the anatomy of elementary surface dynamics at the ultimate space-time limit.

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Measuring Collective Modes With a Multimodal Ultrafast STM

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Measuring the femtosecond dynamics of complex order parameters using a real-space probe has long been a long-coveted goal. To tackle this challenge, over the past decades different variations of pump-probe techniques that integrate pulsed-laser light with an STM have been developed. In this talk I introduce a new multimodal STM-based pump-probe instrument that allows for the measurement of both phonon and carrier dynamics through a combination of time-resolved optical pump-probe reflectance, time-resolved tunneling, and time-resolved point-contact measurements. We apply these techniques to investigate the amplitude and phase excitations in an unconventional charge density wave (CDW) insulator. Specifically, our aim is to detect collective phase oscillations (phasons) in an incommensurate CDW, which gain mass via Coulomb interactions. Although massive phasons were theorized many years ago, only recently has THz emission from the unconventional CDW insulator $(TaSe_4)_2I$ been observed and attributed to this mode. I will present time-domain tunnelling and point-contact measurements revealing 0.22 THz oscillations with temperature dependence consistent with a longitudinal phason acquiring mass via the Higgs mechanism. Interestingly, a second mode at 0.11 THz, with similar intensity, also emerges. Comparison with simultaneous time resolved reflectance data suggests that this is a parametrically amplified, massless transverse phason that competes with and suppresses the amplitudon seen in OPPR at the same frequency. Finally, as time permits, I will demonstrate how ultrafast STM can be used to capture spatially resolved dynamics of step edges that host a one-dimensional edge mode in the topological crystalline insulator $PbSn_xSe_{1-x}$.

Probing Magnon and Phonon Dynamics with Fast Electrons

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Ultrafast microscopy traditionally relies on optical pumping to probe nonequilibrium dynamics. However, many microelectronic and neuromorphic applications operate via electrical triggering. Here, I present our recent advances in all-electric ultrafast electron microscopy, combining electric pumping with electron probing. Sub-picosecond electron pulses are generated using a transverse RF-driven ultrabroadband traveling-wave stripline that sweeps the beam across a chopping aperture. A second, phase-synchronized stripline restores the beam trajectory and momentum, with pump–probe timing controlled through RF phase control.

Using this approach, we directly visualize magnon (spin-wave) dynamics in topological spin textures consisting of vortex–antivortex pairs and intricate domain walls, generated in a microwave-driven transmission electron microscope. Spin waves are observed to nucleate, propagate, reflect, and interfere, with preferential emission from topological antivortices correlated with oscillatory domain-wall motion [1].

If time permits, I will also present ultrafast electron diffraction measurements of phonon dynamics in a two-dimensional charge density wave system under femtosecond laser excitation. Quantitative diffuse scattering analysis reveals the emergence of one-dimensional CDW defects within 1 ps, driven primarily by nonthermal longitudinal optical phonons rather than suppression of the order-parameter amplitude [2].

These results demonstrate the capability of fast, high-energy electron probes to resolve magnon and phonon dynamics, opening new opportunities for studying nonequilibrium quantum materials and advancing electrically controlled spintronic architectures.

Accessing ultrafast structural and electronic phase dynamics at the atomic scale

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Collective excitations and electronic phase transitions in quantum materials unfold at nanometer length scales and femtosecond timescales. Combining ultrafast THz spectroscopy with scanning tunneling microscopy (THz-STM) opens direct access to these dynamics locally at their intrinsic scales. The extreme field enhancement at the STM tip apex concentrates the THz electric field to MV/cm intensities within the tunnel junction. At these field strengths, the THz pulse couples to quantum materials through several distinct mechanisms: THz-induced electron tunneling probes the instantaneous electronic structure with femtosecond precision; sub-picosecond Coulomb forces drive coherent structural dynamics [1]; plasmonic luminescence provides access to time-resolved optical excitations; strong in-plane screening currents locally perturb charge order; and Joule heating deposits energy on ultrafast timescales. This gives THz-STM broad applicability across correlated and quantum materials: In 2H-$NbSe_2$, tip-enhanced THz fields drive in-plane screening currents that locally distort the incommensurate charge-density wave (CDW). Real-space imaging resolves collective phase excitations at sub-THz frequencies emanating at atomic defect sites, revealing how individual impurities govern local CDW dynamics [2]. In 1T-TaS_2, THz pulses manipulate the bilayer stacking order, inducing insulator-to-metal transitions and exposing metastable electronic phases. The commensurate CDW exhibits fast domain reconfigurations, markedly distinct from the defect-pinned slow dynamics in $NbSe_2$. Together, these results show how atomically resolved ultrafast measurements disentangle the microscopic mechanisms of structural and electronic phase transitions in correlated materials.

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Single Atom X-ray Spectroscopy

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Since the discovery of X-rays by Roentgen in 1895, their applications have been ubiquitous, ranging from medical and environmental uses to materials science. X-ray characterization of materials has been revolutionized after the invention of synchrotron X-rays in the mid-20th century. The capabilities of synchrotron light sources have been continuously upgraded, enabling the detection of an atto-gram amount of a sample using X-rays. However, it is still in the range of $\geq$104 atoms or more. Further reducing the material quantity is a long-standing goal, and this talk will present the groundbreaking X-ray spectroscopy and microscopy results of just one atom. Using synchrotron X-rays and a specialized detector tip positioned directly above a single atom in extreme proximity, X-ray excited current in a quantum tunneling regime can be recorded at $\sim$30 K substrate temperature [1]. Indeed, this method can also be applied to detect single-atom signals at room temperature [2]. Using this method, a variety of X-ray spectroscopies, such as X-ray absorption spectroscopies (XAS), near-edge X-ray absorption fine structure (NEXAFS), and X-ray magnetic circular dichroism (XMCD), can be performed on just one atom. Thus, we can now simultaneously determine the elemental, chemical, and magnetic properties of one atom inside a molecule. Moreover, we can now directly image individual atoms with chemical sensitivity using X-ray microscopy. These achievements open a new avenue for material characterization, which will significantly impact various research areas, ranging from environmental and biological sciences to nano and quantum sciences.

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Dynamic magneto-chiral instability in photoexcited tellurium

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In systems of charged chiral fermions out of equilibrium, an electric current parallel to a magnetic field can generate a dynamic instability that amplifies electromagnetic waves. Whether this mechanism also operates in chiral solid-state systems has remained uncertain. Here we observe signatures of a dynamic magneto-chiral instability in elemental tellurium, a structurally chiral crystal, using time-domain terahertz emission spectroscopy. Under transient photoexcitation in a moderate magnetic field, we observe terahertz radiation with coherent modes that grow in amplitude over time. We present a theoretical model that describes this behavior based on a dynamic instability of electromagnetic waves interacting with infrared-active oscillators of acceptor states in tellurium, giving rise to an amplifying polariton. These results demonstrate that magneto-chiral instabilities can emerge in solid-state systems and establish a mechanism for terahertz-wave amplification in chiral materials.

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Floquet Engineering in Valleytronic Materials

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Light-driven control of quantum materials offers powerful pathways for creating nonequilibrium states of matter. Floquet engineering, based on the coherent dressing of solids by time-periodic electromagnetic fields, enables the manipulation of electronic band structures through the amplitude, frequency, and polarization of light. In parallel, valleytronics exploits momentum-space energy extrema as a novel degree of freedom for information processing, where symmetry-governed optical selection rules enable valley-selective excitation.

In this talk, I bridge Floquet engineering and valleytronics by extending symmetry-guided selection rules to hybrid light–matter states. Using a newly developed time- and polarization-resolved extreme-ultraviolet momentum microscope [1], I first demonstrate valley-polarized Floquet–Bloch states in 2H-WSe2 induced by below-bandgap circularly polarized driving [2]. I then establish group-IV transition-metal monochalcogenides as a new valleytronic platform by revealing ultrafast highly anisotropic valley polarization dynamics in SnSe [3]. In this nondegenerate multivalley system, selective excitation into valleys at global conduction minima produces nearly unity and time-independent valley polarization. In contrast, excitation into an alternative valley channel leads to an ultrafast decay and reversal of polarization on sub-picosecond timescales, driven by intervalley scattering mediated through strong electron–phonon coupling with an optical phonon mode. Finally, by extending symmetry-driven Floquet optical selection rules to SnS, I show that the parity of Floquet–Bloch states can be fully controlled through the relative alignment of the drive polarization and crystal axes [4]. These results provide guiding principles for wavefunction symmetry engineering in quantum materials using tailored electromagnetic fields.

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Lightwave electronics in quantum materials

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Petahertz electronics aims to push information processing to the intrinsic timescale of electronic motion by exploiting coherent light–matter interactions [1]. Achieving this goal requires probing and dynamically controlling electronic currents, band structure, topology, and carrier motion on sub-cycle timescales [2-4]. We first demonstrate coherent control in graphene and light-dressed graphene, enabling interferometric manipulation of Bloch electrons and optical control of symmetry and electronic structure at optical frequencies. Intense circularly polarized mid-infrared fields transiently open topological gaps and reshape Berry curvature distributions, allowing sub-optical-cycle steering of valley-selective currents. Time-resolved measurements reveal coherent band dressing and controllable modification of electron dynamics without relying on thermal pathways. By tailoring polarization, waveform, and phase of the driving field, we achieve programmable transient electronic phases and petahertz current generation. In the second part, we use below-bandgap mid-infrared pulses to drive monolayer tungsten disulfide, demonstrating strong-field excitonic dressing exceeding 100 meV [5]. Transient absorption spectroscopy reveals the emergence of a virtual absorption feature below the 1s exciton resonance, which we attribute to a light-dressed sideband of the dark 2p exciton state. Together, these results establish Floquet engineering as a powerful route toward optically defined electronic functionality, where band topology and carrier transport can be controlled within a single optical cycle. This approach bridges ultrafast strong-field physics and condensed matter science, outlining a pathway toward coherent, lightwave-driven electronics operating at fundamentally new speed limits.

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Observation of Floquet states in graphene

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Material phases are traditionally controlled by parameters such as temperature or doping. Newer efforts employ ultrashort light pulses and correlated - but incoherent - interactions of the electron-lattice-spin systems to create non-thermal phases. While such on-demand material engineering has been established in the last years, more recent efforts strive for the coherent counterpart: By using time-periodic light fields (a.k.a Floquet engineering), new electronic band structures and correlated or even topological phases can be created. Importantly, these phases can then be coherently controlled by the properties of the light field. Therefore, fundamental research on Floquet engineering promises the realization of emergent material phases without any counterpart in thermal equilibrium.

Here, we will outline how the development of time-resolved momentum microscopy [1,2] - a new variant of time- and angle-resolved photoelectron spectroscopy - has enabled the direct observation of Floquet states in monolayer graphene [3]. These proof-of-principle experiments on semi-metallic graphene open up a new pathway for testing the many theoretical proposals of light-induced phase transitions that have so far remained elusive.

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Discovery of 3D Floquet-Bloch Bands

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Periodically driving a solid with light can fundamentally modify its electronic properties, giving rise to novel non-equilibrium phases known as Floquet-Bloch states. While these states have been extensively demonstrated in (quasi-)two-dimensional (2D) electronic band structure, their realization in three-dimensional (3D) bulk bands has remained largely unexplored.In this work, using time- and angle-resolved photoemission spectroscopy (tr-ARPES), we report the observation of 3D Floquet-Bloch bands in MBE-synthesized PbSe thin films. We demonstrate that the observed replica bands exhibit distinct, replica order dependent dispersion and hybridization, which can be quantitatively corroborated by theoretical models incorporating the k_z-dependence of the electronic structure. Our finding intrinsically distinguishes 3D Floquet-Bloch states from laser-assisted photoemission (Volkov states), which typically exhibit identical dispersions across different replica orders, and establish a pathway for the Floquet engineering of 3D topological phases.

Imaging Exciton Transport and Quantum Interactions with Ultrafast Microscopy

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At the most fundamental level, transport of energy carriers (such as electrons and excitons) in the solid state is determined by their wavefunctions and the interactions with the lattices and the environment. Wave properties of these particles have profound consequences in their transport. The key difficulties in probing transport in the quantum regime in real materials lie in the fast (picosecond or shorter) dephasing processes and the nanoscale localization lengths. Thus, to image the motion of excitons in their natural (quantum) time and length scales, experimental approaches combining spatial and temporal resolutions are necessary.

To address this challenge, my research group has developed the combined use of optical microscopy and ultrafast spectroscopy tools to image transport of excitons from the nanoscale to the mesoscale and over a wide range of temperatures. In my talk, I will discuss our recent progress on imaging environment-assisted quantum exciton transport in perovskite quantum dot superlattices and quantum phase transition of moiré excitons. These results provide fundamental understandings of how excitons migrate in materials and how these processes can be manipulated quantum mechanically. The unique ability to measure and control coherent pathways are critical for both solar energy and quantum information applications.

Coherent Exciton–Magnon–Photon Interaction in van der Waals Magnetic Semiconductors

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Van der Waals (vdW) magnetic semiconductors, where excitonic states are strongly coupled to the underlying magnetic order, provide a compelling platform for studying coherent interactions among magnons, excitons, and photons. In this talk, I will present our work on the layered magnetic semiconductor CrSBr, which hosts self-hybridized exciton–polaritons that exhibit signatures of coherent magnon oscillations [1]. I will also discuss how magnons can mediate nonlinear exciton–exciton interactions in this material, highlighting a pathway toward magnetically controlled optical nonlinearities [2]. Finally, I will present results of microwave spectroscopy and discuss the prospects for using this system as a platform for microwave-to-optical quantum transduction.

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Many-body effects in photoemission and nonlinear optics of 2D materials

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By now, exciton effects in the linear response regime in low-dimensional materials are well understood, but quantitative prediction of the dynamics of these excited states and their evolution under intense or ultrafast pulses of light remains a significant challenge. The first-principles understanding of exciton dynamics requires a few basic building blocks: the full exciton dispersion, which governs the phase space for momentum- and energy-conserving scattering processes; the coupling of excitons to external perturbations such as electromagnetic fields and lattice vibrations; and equations of motion capable of describing the resulting real-time dynamics. In this talk, I will discuss some of my group's recent theoretical and computational developments in these directions. I will highlight our recent observation of exciton dispersion in a 2D material, revealing for the first time a linearly dispersing exciton formed from electrons and holes in parabolic bands [1]. I will also discuss recent work on excitonic effects in time- and angle-resolved photoemission (TR-ARPES), including signatures of excitons in moiré heterostructures [2] and topological materials, as well as signatures of trions and other multiparticle excitations.

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Exciton Dressing by Extreme Magnon Nonlinearities

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The nonlinear dynamics of collective excitations offer both intriguing fundamental phenomena and significant practical applications. Demonstration of the frequency mixing processes seen in nonlinear optics in other quasiparticles holds considerable potential for practical applications in phononics and magnonics, emerging fields that leverage collective excitations for novel material control and coherent information transfer. In this talk, I will demonstrate the optical generation and detection of abundant magnonic frequency mixing processes in the antiferromagnetic semiconductor CrSBr by employing above-gap pump pulses to launch coherent magnons and optically measuring them via strong magnon-exciton coupling. The data shows a series of magnon sidebands arising from high-harmonic generation and, when breaking the system symmetry, the mixing of discrete magnon modes to produce sum and difference frequency generation (SFG & DFG). Further, we demonstrate control over the DFG in CrSBr by rotating an external magnetic field to tune its frequency over a broad range. This tuning allows us to push the DFG mode into resonance with one of the fundamental magnon modes, where we can controllably induce parametric amplification. Finally, I will show how we can generate broad magnonic frequency combs, opening a pathway to GHz magnonic metrology and spectroscopy. These findings herald the opening of a new domain in nonlinear opto-magnonic coupling, offering innovative functionalities for hybrid quantum magnonics.

Directly probing non-equilibrium dynamics of momentum-indirect dark interlayer excitons

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Interlayer excitons (IXs), formed by electrons and holes residing in different layers of van der Waals heterostructures, have emerged as an attractive platform to study valleytronics, twistronics, as well as new exciton physics. Recently, new types of interlayer excitons such as quadrupolar excitons and every-other-layer excitons have been found in heterostructures containing transition metal dichalcogenide (TMD) multilayers [1]. However, due to the naturally indirect bandgap of multilayer TMDs, the lowest-energy excitonic states in heterostructures are momentum-dark states, which could significantly influence exciton formation and decay dynamics. Thus, a full understanding of these new types of excitons requires direct observation of momentum-dark states, which cannot be accessed by general optical probes. Time- and angle-resolved photoemission spectroscopy is a powerful tool to directly visualize momentum-dark exciton states [2].

In this work, by employing time-resolved momentum microscopy with XUV pulses at a 61 MHz repetition rate [3], we study the non-equilibrium dynamics of a momentum-dark interlayer exciton state in a model $3LWS_2/1LWSe_2$ system. We find that excitons in the K valley are quickly transferred to the Σ valley and form long-lived momentum-indirect dark interlayer excitons after initial above-gap photoexcitation, evidenced by the rapid decay of the K exciton and delayed rise of the Σ exciton. A full view of momentum-dark interlayer exciton formation is achieved by measuring the momentum- and energy-resolved photoelectron distribution. The change in the photoelectron dispersion clearly resolves the conversion of initially hot exciton states to the final lowest-energy dark exciton states.

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Cavity electrodynamics of van der Waals heterostructures

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Van der Waals (vdW) heterostructures host many-body quantum phenomena that can be tuned in situ using electrostatic gates. These gates are often microstructured graphite flakes that naturally form plasmonic cavities, confining light in discrete standing waves of current density due to their finite size. Their resonances typically lie in the GHz - THz range, corresponding to the same μeV - meV energy scale characteristic of many quantum effects in the materials they electrically control. This raises the possibility that built-in cavity modes could be relevant for shaping the low-energy physics of vdW heterostructures. However, capturing this light-matter interaction remains elusive as devices are significantly smaller than the diffraction limit at these wavelengths, hindering far-field spectroscopic tools. Here, we report on the sub-wavelength cavity electrodynamics of graphene embedded in a vdW heterostructure plasmonic microcavity. Using on-chip THz spectroscopy, we observed spectral weight transfer and an avoided crossing between the graphite cavity and graphene plasmon modes as the graphene carrier density was tuned, revealing their ultrastrong coupling. Our findings show that intrinsic cavity modes of metallic gates can sense and manipulate the low-energy electrodynamics of vdW heterostructures. This opens a pathway for deeper understanding of emergent phases in these materials and new functionality through cavity control.

On-Chip Hybrid System for Cavity-Driven Floquet States

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Engineering the electromagnetic environment of emergent quantum phenomena via THz and optical cavities has emerged as a crucial new knob for tailoring designer's quantum materials. Cavity Floquet engineering has been shown to enhance the optical Stark effect in 2D materials. To fully unlock the potential of cavity Floquet engineering, the direct signature of cavity-driven Floquet states as well as their time- and energy-domain distributions are yet to be experimentally elucidated in the single-particle spectral function. Here, we engineer and probe cavity-driven Floquet states by integrating an ultrathin topological insulator film onto a photonic crystal cavity. By pumping the hybrid system with ultrafast mid-infrared light pulses with a pulse duration of 250 fs full-width-half-maximum, we observe a coherent Floquet state lasting for at least 1 ps using time- and angle-resolved photoemission spectroscopy. In the meantime, the maximum internal electronic energy of the topological insulator in the cavity region is approximately doubled compared to that on a plain silicon-on-insulator wafer. Our results establish the feasibility of on-chip integration of topological materials and photonic devices, and can be quantitatively modeled by a driven cavity coupled to a thermal bath. The extracted equivalent Q factor is in the range of 100-200, and can be optimized by orders of magnitude with an improved quality of the heterogeneous system and an enhanced far-field coupling. Our work provides a clear path toward on-chip manipulation of Floquet physics.

Imaging a terahertz superfluid plasmon in a two-dimensional superconductor

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Many fundamental excitations in solids, such as lattice vibrations, collective electron motion, and spin dynamics, naturally evolve on picosecond timescales and meV energy scales. Terahertz (THz) spectroscopy, which directly matches these intrinsic scales, has therefore become a powerful tool to probe their dynamics. However, its poor spatial resolution, limited by the 100 mum THz wavelength, constrains its application to the rapidly growing field of low-dimensional materials. We overcome this limitation by placing the sample in direct contact with a microscopically small spintronic THz emitter. The emitter is driven by a tightly focused ultrashort near-infrared laser pulse, which defines the sub-wavelength spatial extent of the THz near field. In this configuration, the confined THz radiation interacts with the sample before diverging into the far field. Using this approach, we study how tailoring the THz light–matter interaction through the sample's geometry and dielectric environment gives rise to distinct resonances that confine electromagnetic waves to deeply sub-wavelength scales. We observe clear spectroscopic evidence of a below-gap, two-dimensional superfluid plasmon in few-layer $Bi_2Sr_2CaCu_2O_{8+x}$ and spatially resolve its sub-diffractive electrodynamics. This resonance, absent in bulk and emerging only below the superconducting transition ($T_c = 87$ K), is visualized by raster scanning the confined THz source across the sample. These measurements directly capture the momentum- and frequency-dependent evolution of the superconducting transition in two dimensions and open a pathway to deterministically probe and control THz light–matter coupling in quantum materials, bridging the domains of cavity quantum electrodynamics and low-dimensional condensed matter.

Polariton Conversion in isotope-enriched hexagonal BN revealed by AFM-2DIR

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In this talk, we introduce atomic-force-microscopy-based time-domain two-dimensional infrared (AFM-2DIR) spectroscopy, a surface nanospectroscopy that combines the sub-10 nm spatial resolution of AFM with the rich spectroscopic information of 2DIR. By mechanically detecting photothermal responses to tip-enhanced femtosecond IR pulse sequences, AFM-2DIR enables nanoscale probing of vibrational anharmonicity, mode coupling, and energy transfers in heterogeneous materials.

In this work, we apply AFM-2DIR to investigate hyperbolic phonon polaritons (PhPs) in isotope-enriched hexagonal boron nitride (hBN), a 2D material renowned for supporting high-momentum, low-loss polaritons in the mid-IR range. Using AFM-2DIR, we map PhP interference fringes on a 40-nm-thick hBN flake, confirming the dispersion relation and mode accessibility via tip-launched near-field photons. The AFM-2DIR spectra reveal diagonal features corresponding to PhP modes (m=0,1,2...) near the phonon resonance at 1,390 cm^{-1}, with off-diagonal asymmetries indicating causality-driven energy transfers. Notably, we uncover polariton-to-phonon conversion, manifesting as negative off-diagonal features linking PhP clusters at 1,405 cm^{-1} to the phonon mode, likely via phonon scattering. Additionally, positive off-diagonal peaks signify inter-polariton conversions, explained by a propagation-scattering model where PhPs at different frequencies (ω_1, ω_2) form closed paths, with scattering amplified at flake edges and interfaces.

These findings elucidate ultrafast relaxation pathways in hBN, including picosecond-scale energy dissipation and mode interactions, with implications for nano-optical devices, subwavelength imaging, and polaritonic energy transport. AFM-2DIR thus opens avenues for in situ studies of surface dynamics in 2D materials at IR frequencies.

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Ultrafast Light-Induced Magnetoelectric Effect in van der Waals Magnetic Semiconductor Heterostructures

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Atomic-scale heterostructures of van der Waals (vdW) magnets and semiconductors provide a unique environment for exploring magnetic dynamics. In contrast to typical photothermal excitation of precessional magnetization dynamics by a pump laser pulse, we find that ultrafast optical excitation of a $WS_2/CrGeTe_3$ (CGT) bilayer produces an opposite sign of magnetic torque compared to an isolated CGT film. Experimental observations by time-resolved magneto-optic Kerr effect (TR-MOKE) [1] and theoretical analysis by density functional theory (DFT) and Landau-Lifshitz-Gilbert (LLG) simulations support a mechanism in which charge transfer of photoexcited carriers across the interface alters the perpendicular magnetic anisotropy, which in turn generates a torque on the magnetic layer to trigger precessional magnetization dynamics. These results provide new avenues for ultrafast manipulation of magnetization in vdW heterostructures with type-II band alignments. Lastly, we show that optically-generated spin currents from WS_2 into CGT can also trigger precessional dynamics, although the amplitude is relatively small.

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Attosecond K-space and Time-Resolved Momentum Microscopy of Graphite(0001) at the Extreme Light Infrastructure

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Momentum-resolved photoemission electron microscopy (PEEM) was employed to investigate photoemission from single-crystalline graphite(0001), with the aim of disentangling the respective roles of occupied valence bands and unoccupied final-state conduction channels in shaping the photoelectron angular distributions. Time-resolved photoemission serves as a highly effective method for exploring surface electron dynamics. Our NanoESCA end station is attached to a high-harmonic generation (HHG) beamline, and time-resolved momentum microscopy can be performed in a pump-probe scheme. To illustrate the performance of our user-ready system, the first results obtained by the RABBITT (Reconstruction of Attosecond Beating By Interference of Two-photon Transitions) scheme are presented. This experiment examined a graphite(0001) single crystal, revealing RABBITT oscillations across the entire Brillouin zone with attosecond accuracy, presented as a time-resolved momentum-space movie. This series of time-resolved experiments will reveal how photoemission dynamics are affected by the polarization of the excitation source and how the timing of photoelectrons from different valence band regions, governed by distinct selection rules for optical transitions, influences the measured photoemission time delays.

Ultrafast Optoelectronic Gating and Band-Gap Renormalization in Bilayer Graphene

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Using femtosecond time- and angle-resolved photoemission spectroscopy, we investigate photoinduced interlayer charge-transfer dynamics in a heterostructure composed of Bernal-stacked bilayer graphene and a monolayer of silver on 6H-SiC(0001) [1]. We show that optical excitation transiently modifies the intrinsic potential landscape across the silver–graphene interface, effectively acting as an ultrafast optoelectronic gate. This leads to momentum-dependent band renormalizations and induces a transient band-gap opening on femtosecond timescales. Concurrently, the presence of photogenerated hot carriers enhances electronic screening, resulting in a subsequent closing of the band gap beyond its thermal equilibrium value. Our results identify interlayer charge transfer and hot-carrier–enhanced screening as two distinct mechanisms enabling reversible, photoinduced control of the electronic band structure in bilayer graphene, providing a pathway toward ultrafast manipulation of electronic properties in graphene-based heterostructures under non-equilibrium conditions.

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Delayed Lattice Heating by Mode-Selective Electron–Phonon Coupling

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Ultrashort laser pulses enable controlled manipulation of matter on femtosecond timescales. Following optical excitation, energy is rapidly deposited into the electronic subsystem and subsequently transferred to the lattice, potentially driving structural transitions such as melting and ablation. The rate of this energy exchange, typically described by the electron–phonon coupling parameter, sets the timescale of lattice heating and thus governs the onset of phase transitions.

The nonequilibrium between electrons and phonons is often described by a two-temperature model, which assumes that both subsystems can be represented by separate thermal distributions and, in particular, that the lattice instantaneously equilibrates internally. However, recent experimental studies in metals have revealed strongly mode-selective phonon excitation, with Brillouin-zone-boundary phonons exhibiting significantly higher populations than predicted by a thermal distribution [1,2].

In this work, we numerically trace the formation of such nonequilibrium "hot phonons" and quantify their impact on electron–phonon energy exchange using Boltzmann collision integrals. We demonstrate that selectively excited phonons transiently transfer energy back to the electronic subsystem, effectively slowing electron–phonon equilibration [3]. Our results indicate the need to move beyond thermally equilibrated lattice models for a predictive description of ultrafast laser-driven phase transitions.

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Non-thermal phonon dynamics of various layered materials

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Layered materials are promising platforms for exploring correlated phenomena, and their carrier dynamics have been extensively studied using ultrafast pump-probe techniques. In contrast, the structural evolution of their surface layers remains largely unexplored. Ultrafast low-energy electron diffraction (ULEED) addresses this gap by combining surface sensitivity with temporal resolution down to 1-2 ps [1]. Building on this, we recently demonstrated that transient changes in the diffuse scattering background allow momentum-resolved tracking of phonon populations with out-of-plane polarization across the Brillouin zone [2].

Here, we apply this approach to investigate the phonon buildup in a range of layered materials, including the transition metal dichalcogenides $TiSe_2$ and WTe_2, as well as the Kagome metal CsV_3Sb_5. We generally find a rapid accumulation of non-thermal phonons near the Brillouin-zone boundaries, followed by a slower emergence of zone-center acoustic modes. These weakly coupled phonons substantially delay overall lattice equilibration, underscoring the critical role of phonon-phonon scattering in energy redistribution. Our results provide a detailed, momentum-resolved picture of non-equilibrium phonon dynamics in layered systems, offering new insights for controlling ultrafast energy flow and lattice responses in low-dimensional materials.

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Dynamic Competition Between Superconductivity and Pseudogap in the Dark Electronic Side of Cuprates

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The time- and angle-resolved photoemission (TR-ARPES, [1]) endstation at the Advanced Laser Light Source (ALLS) facility enables detailed investigations into the low-energy electrodynamics of quantum materials with high energy and momentum resolutions. By combining sample voltage bias and a hemispherical analyser with deflector technology, we have access to a significant fraction of the momentum space of quantum materials, even with low photon energy photons [2]. Here, I will present novel high-resolution TR-ARPES studies of optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). First, I will provide direct evidence that light excitation disrupts long-range superconducting order by scrambling the phase coherence of the superconducting condensate [3]. Then, by focusing on the near-antinodal region of Bi2212, I will present evidence of a light-induced asymmetric pseudogap-like density of states at electronic temperatures well below the equilibrium superconducting critical temperature [4]. These experimental results, supported by phenomenological theory, demonstrate our ability to uncover the dynamic interplay and competition between superconducting and pseudogap states by tracking the transfer of spectral weight in the near-antinodal dark electronic states of cuprates.

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