O 66: Ultrafast electron dynamics at surface and interfaces III

Time: Wednesday 15:00–17:45 Location: TRE/MATH

Invited Talk O 66.1 Wed 15:00 TRE/MATH

Ultrafast exciton dynamics in 2D semiconductors and electric field gated devices — •Jan Philipp Bange — Georg-August-Universität Göttingen, I. Physikalisches Institut, Germany

Two-dimensional (2D) semiconductors and moiré materials, formed by stacking and twisting atomically thin layers, provide an exciting platform to discover and engineer new quantum states. Precise and reversible control of carrier density and many-body effects is readily achieved through in-situ electric field gating. In combination with angle-resolved photoemission spectroscopy this has been a powerful probe of the static electronic band structure. However, capturing the ultrafast dynamics of excited states in gated 2D materials, including hybrid excitons [1], interlayer excitons [2], and trions [3], remains a fundamental challenge due to the limited real-space resolution of ultrafast time- and momentum-resolved spectroscopy techniques. In this talk, I will present how time-resolved momentum microscopy provides direct access to both the energy landscape and femtosecond dynamics of bright and dark excitons at nanometer length scales. This methodology enables the disentanglement of electron and hole transfer pathways across twisted transition metal dichalcogenide interfaces and reveals the ultrafast formation of quasiparticles as a function of gate voltage.
[1] Bange *et al.*, Science Advances **10**, eadi1323 (2024).
[2] Schmitt *et al.*, Nature Photonics **19**, 187 (2025).
[3] Meneghini *et al.*, arXiv.2511.11448 (2025).

O 66.2 Wed 15:30 TRE/MATH

Ultrafast signatures of Dirac - flat-band hybrid states from time-resolved ARPES — •Maria-Elisabeth Federl[1], Johannes Gradl[1], Franziska Bergmeier[1], Zamin Mamiyev[2], Niclas Tilgner[2], Thomas Seyller[2], Christoph Tegenkamp[2], and Isabella Gierz[1] — [1]University of Regensburg — [2]Chemnitz University of Technology

Hybridization of highly itinerant Dirac electrons with localized flat-band states is predicted to yield emergent phenomena such as exotic heavy-fermion behaviour. Epitaxial graphene resting on a flat-band system at the graphene-SiC(0001) interface offers a promising platform, yet direct spectroscopic signatures - such as avoided crossings in equilibrium ARPES - have remained unresolved. We solved this problem using time-resolved ARPES where evidence of hybridization manifested in three key observations: (1) accelerated Dirac-carrier relaxation due to an increased scattering phase space, (2) transient charging of the Dirac cone enabled by direct optical excitation from the flat bands, and (3) ultrafast charge transfer back into the flat bands on timescales set by the interlayer coupling strength. Our results thus provide a clear dynamical fingerprint of hybridization in a system where equilibrium probes have proven inconclusive.

O 66.3 Wed 15:45 TRE/MATH

Probing topological Floquet states in graphene with ultrafast STM — •Nils Jacobsen[1,2], Melanie Müller[3], Michael Schüler[4,5], Martin Wolf[3], and Angel Rubio[2,6] — [1]University of Bremen — [2]MPSD Hamburg — [3]FHI Berlin — [4]PSI Villingen Switzerland — [5]University of Fribourg Switzerland — [6]CCQ The Flatiron Institute New York USA

The light-induced anomalous Hall effect in graphene driven by circularly polarized light is a hallmark example of Floquet band engineering [1]. It has been observed in ultrafast transport experiments [2] and Floquet Bloch bands in graphene have recently been resolved by time- and angle-resolved photoemission spectroscopy [3]. Here, we propose ultrafast scanning tunnelling microscopy (USTM) as a complementary probe of topological Floquet states in graphene [4]. In our simulations, dynamical band gaps and topological edge states are directly reflected in the local density of states and the ultrafast tunnelling currents. The chirality of the edge states is revealed by the suppression of backscattering at impurities, which could be probed by ultrafast STM. These results establish ultrafast STM as a promising tool to access light-induced topological states in quantum materials. [1] Oka PRB 79, 081406(R) (2009) [2] McIver Nat. Phys. 16, 38-41 (2020) [3] Merboldt, Schüler et al. Nat. Phys. 21 1093-1099 (2025), Choi, Mogi et al. Nat. Phys. 21 1100-1105 (2025) [4] Müller Prog. Surf Sci. 99, 100727 (2024)

O 66.4 Wed 16:00 TRE/MATH

Ultrafast Band-Gap Renormalization in Bilayer Graphene — •Eduard Moos[1], ZhiYuan Deng[1], Hauke Beyer[1], Arpit Jain[4], Chengye Dong[4], Joshua A. Robinson[4], Kai Rossnagel[1,2,3], and Michael Bauer[1,2] — [1]Kiel University, Germany — [2]Kiel Nano, Surface and Interface Science KiNSIS, Germany — [3]Electron Synchrotron DESY, Germany — [4]Pennsylvania State University, United States

We demonstrate, by femtosecond time- and angle-resolved photoemission spectroscopy, that photoinduced interlayer charge transfer in a heterostructure consisting of Bernal-stacked bilayer graphen and a single atomic layer of silver on 6H-SiC(0001) transiently modulates the intrinsic potential landscape across the silver-graphene interface. Acting as an ultrafast electronic gate, this drives momentum-dependent band renormalizations, resulting in a transient band-gap opening on femtosecond timescales. Simultaneously, the photogenerated hot-carrier population enhances electronic screening, leading to a subsequent closing of the band-gap beyond the thermal equilibrium value. These findings reveal two different mechanisms for a photoinduced, reversible control of the electronic band structure in bilayer graphen — interlayer charge transfer and hot-carrier enhanced screening — providing a general framework for the ultrafast control of electronic properties in graphene-based heterostructures. They further open novel pathways for the realization of ultrafast optoelectronic devices and the exploration of correlated quantum phases in bilayer graphene under nonequilibrium conditions.

O 66.5 Wed 16:15 TRE/MATH

Attosecond spin-orbit delays in solid-state photoemission — •Andreas Gebauer[1], Walter Enns[1], Sergej Neb[2], Tillmann Schabbehard[1], Luis Maschmann[1], J. Hugo Dil[3], Ulrich Heinzmann[1], Stephan Fritzsche[4,5,6], Nikolay M. Kabachnik[7,8], Eugene E. Krasovskii[8,9,10], and Walter Pfeiffer[1] — [1]Bielefeld University — [2]ETH Zurich — [3]EPFL, Lausanne — [4]Helmholtz Institute Jena — [5]GSI Helmholtzzentrum für Schwerionenforschung GmbH — [6]Friedrich-Schiller-University Jena — [7]European XFEL GmbH, Schenefeld — [8]DIPC, San Sebastián — [9]Universidad del País Vasco, San Sebastián — [10]IKERBASQUE, Bilbao

Attosecond time-resolved photoelectron spectroscopy allows observation of photoemission dynamics in solids on its natural time scale. Photoelectrons typically need tens to hundreds of attoseconds to be released into the vacuum while various competing effects determine the emission dynamics. We report the first observation of unexpectedly large spin-orbit delays, i.e. relative photoemission delays between spin-orbit split core levels in Bi_2Te_3 and Bi_2Se_3. The observed delays can neither be attributed to intra-atomic delays nor to ballistic photoelectron transport. Instead, calculations based on one-step photoemission theory reveal that strong variations of the final state wave function on the energy scale of the spin-orbit splitting are responsible for the experimental observation. These variations reflect the complex interplay of propagating and evanescent waves in the photoelectron emission, exhibiting qualitatively different emission dynamics.

O 66.6 Wed 16:30 TRE/MATH

Electron Correlations in Ultrafast Transmission Electron Microscopy — •Nico Stumpp[1], Andreas Wendeln[1], Alexander Schröder[1], and Sascha Schäfer[1,2] — [1]Department of Physics, University of Regensburg, Regensburg, Germany — [2]Regensburg Center for Ultrafast Nanoscopy (RUN), Regensburg, Germany

Ultrafast transmission electron microscopy (UTEM) strives to combine an atomic spatial resolution with a femtosecond temporal resolution, yet its performance is inherently limited by Coulomb repulsion within electron pulses. Research in free-electron quantum optics suggests that, rather than avoiding these dynamic interactions, exploiting their induced inter-electron correlations offers a pathway toward quantum-limited imaging performance [1,2].

Utilizing an event-based electron detector with nanosecond temporal resolution, we observe pronounced energy anti-correlations in few-electron states emitted from a high-coherence, laser-driven cold field-emission electron source [3]. Crucially, we demonstrate the ability to actively modify the magnitude and visibility of the induced energy separation depending on angular post-selection. We complement our experimental results with numerical multi-particle simulations of electron

pulse dynamics within the electrostatic gun environment, focussing on the interplay between strongly interacting correlated electron pairs and the surrounding electron ensemble of the emitted photoelectron bunch.

[1] R. Haindl et al., Nat. Phys. 19, 1410 (2023).
[2] S. Meier et. al., Nat. Phys. 19, 1402 (2023).
[3] A. Schröder et al., Ultramicroscopy 275, 114158 (2025).

O 66.7 Wed 16:45 TRE/MATH

Ultrafast Investigation of Competing CDW Orders in $LaTe_3$ — •Francesco Sammartino[1], Wibke Bronsch[2], Fulvio Parmigiani[1,2], and Federico Cilento[2] — [1]Università degli Studi di Trieste — [2]Elettra - Sinctrotrone Trieste

The RTe_3 family hosts a rich landscape of charge-density-wave (CDW) phases. All members display a unidirectional CDW aligned along the *c*-axis, while only the heavier rare-earth compounds develop an additional equilibrium CDW along the *a*-axis at lower temperature. Intriguingly, recent ultrafast experiments have shown that $LaTe_3$, whose equilibrium state features only the *c*-axis CDW, can transiently exhibit a rotated CDW component oriented along the *a*-axis.

Building on time-resolved optical studies that first revealed the emergence of this orthogonal order, we investigated $LaTe_3$ through time-resolved ARPES (TR-ARPES) to track, with momentum resolution, the ultrafast evolution of its electronic structure.

We monitored the melting of the equilibrium *c*-axis CDW gap and searched for transient modifications of the electronic dispersions along the *a*-axis that could be linked to the emergence of the rotated order. This study provides direct insight into the nonequilibrium CDW dynamics of $LaTe_3$ and may help clarify the microscopic pathways that enable the formation of the rotated CDW state.

O 66.8 Wed 17:00 TRE/MATH

Electron and exciton dynamics in large-angle twisted bilayer graphene — •Gianmarco Gatti[1], Anders Mortensen[1], Gesa Siemann[1], Zhihao Jiang[1], Alfred Jones[1], Chakradhar Sahoo[1], Thomas Nielsen[1], Naina Kushwaha[2], Jennifer Ridgen[2], Søren Ulstrup[1], Bruce Weaver[2], Yu Zhang[2], Charlotte Sanders[2], Emma Springate[2], Vibha Reddy[3], Ulrich Starke[3], and Philip Hofmann[1] — [1]Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark — [2]Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, Oxfordshire OX11 0QX, UK — [3]Max Planck Institute for Solid State Research, Heisenbergstr. 1, 70569, Stuttgart, Germany

Tunable moiré superlattices naturally form in artificially stacked monolayers through control of their rotational misalignment (twist angle). In large-angle twisted bilayer graphene (TBG), orbital hybridization between the monolayer-derived π/π^* bands leads to avoided crossings and the emergence of pairs of occupied and unoccupied van Hove singularities at fixed wave vectors k*. We investigate the out-of-equilibrium electron dynamics near these points in 10°-TBG using IR-pump XUV-probe time-resolved ARPES experiments. Our measurements resolve the hot electron dynamics in TBG and reveal an additional, unexpected spectral weight within the local electronic band gap at k*. This observation is consistent with the signature of a strongly bound exciton in TBG, whose formation has been attributed by recent theoretical models to a unique destructive coherence between two energy-degenerate subband resonant transitions.

O 66.9 Wed 17:15 TRE/MATH

Hybrid Frenkel-Wannier excitons facilitate ultrafast energy transfer at a 2D-organic interface — •Wiebke Bennecke[1], Ignacio Gonzalez Oliva[2], Jan Philipp Bange[1], Paul Werner[1], David Schmitt[1], Marco Merboldt[1], Anna M. Seiler[1], Daniel Steil[1], R. Thomas Weitz[1], Peter Puschnig[3], Claudia Draxl[2], G. S. Matthijs Jansen[1], Marcel Reutzel[1], and Stefan Mathias[1] — [1]I. Physikalisches Institut, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany — [2]Physics Department and CSMB, Humboldt-Universität zu Berlin, 12489 Berlin, Germany — [3]Institute of Physics, NAWI Graz, University of Graz, 8010 Graz, Austria

The combination of two-dimensional transition metal dichalcogenides (TMDs) and organic semiconductors (OSCs) is a highly promising material platform for the realization of future optoelectronic devices. While the excitonic properties of their individual components have been intensively studied, much less is known about excitons at the hybrid interface. Here, we use ultrafast momentum microscopy and many-body perturbation theory to investigate the exciton landscape at the PTCDA/WSe_2 interface [1]. In particular, we find an exciton state formed via Förster resonant energy transfer, which is of hybrid nature: Concomitant intra- and interlayer electron-hole transitions within the OSC layer and across the TMD/OSC interface, respectively, give rise to an exciton wavefunction with mixed Frenkel-Wannier character.

[1] Bennecke *et al.*, Nat. Phys. (2025)

O 66.10 Wed 17:30 TRE/MATH

Electronic friction simulations of laser-driven hydrogen evolution from copper. Does surface coverage matter? — •Alexander Spears[1], Wojciech G Stark[2], and Reinhard J. Maurer[1,3] — [1]University of Vienna, AT — [2]Imperial College London, UK — [3]University of Warwick, UK

Plasmonic catalysts such as metal nanoparticles harness the energy transfer between light, electrons and phonons at interfaces to drive chemical reactivity at interfaces. However, even on clean metal surfaces with a regular structure, it is unclear whether these dynamics are the result of mode-selective energy transfer or photothermal heating effects. Molecular dynamics simulations with electronic friction (MDEF) offer a quantum-classical description of electron-phonon coupling and have previously been used to model ultrafast dynamics on metal surfaces. Using machine learning surrogate models to accelerate MDEF simulations, we show that mode-selective energy transfer has a negligible influence on light-driven hydrogen evolution from copper surfaces. By comparing energy partitioning in desorbed molecules, we conclude the choice of electronic friction approximation only determines the rate of energy transfer, while the energy distributions of desorbing molecules are governed by the potential energy surface. This suggests that thermal and laser-driven desorption may yield similar outcomes at low coverage. However, we expect mode-selective energy transfer to play a stronger role at higher coverage, and show preliminary results for surface coverage dependence in laser-driven desorption.