HL 3: 2D Materials I – Excitonic properties

Time: Monday 9:30–12:45 Location: POT/0081

HL 3.1 Mon 9:30 POT/0081

Exciton-Electron Complexes in Multilayer Transition-Metal Dichalcogenides — •Florian Hirsch[1], Alexandra Hübler[1], Jonas von Milczewski[2], and Richard Schmidt[1] — [1]Institute for Theoretical Physics, Heidelberg University, Philosophenweg 16, 69120 Heidelberg, Germany — [2]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Understanding few-body correlations in van der Waals heterostructures is essential for uncovering emergent electronic phases in layered quantum materials. We report recent progress in identifying exciton-electron-electron bound states in multilayer transition-metal dichalcogenides (TMDs). Starting from the two-body problem, we employ complementary theoretical approaches to characterize bound states and systematically extend this framework to the four-body regime. Within an effective-mass model, we solve the resulting few-body Hamiltonians using exact diagonalization, enabling efficient exploration of material and geometric parameters. This allows us to map out regimes in which such exciton-electron complexes become bound. Our results provide a versatile framework for investigating exciton-mediated correlations in complex multilayer TMD structures and related systems, including platforms where exciton-induced electron pairing or superconductivity may emerge.

HL 3.2 Mon 9:45 POT/0081

Intra- and Interlayer Excitons in TMDC bilayers under external influence — •Jan-Hauke Graalmann and Michael Rohlfing — University of Münster, Institute of Solid State Theory, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany

External influences lead to several changes in the optical spectrum of TMDC bilayers obtained by solving the Bethe-Salpeter. We discuss both the effect of applied pressure and that of an electric field [1,2].

To get the deformation induced by applied pressure, we use Hooke's law. In this case, our investigations show an effective shift of the intralayer A exciton whose direction depends on the stress conditions and we observe a similar behavior for the interlayer exciton, while the shift rate is smaller for the latter. Our results for the 2H-MoS_2 bilayer compare very well with available room-temperature measurements for the interlayer exciton.

An electric field applied perpendicular to the 2H-$MoSe_2$ bilayer does not lead to a deformation, but instead to a Stark shift of the excitons. To explain that, we focus on the lifting of the degeneracy in the band structure by breaking the symmetry of the potential.

[1] P. Steeger, J. Graalmann et al., nano Lett., 23, (2023)
[2] J. Jasiński et al., Nat Commun 16, 1382, (2025)

HL 3.3 Mon 10:00 POT/0081

Optical probing of the gate-tunable electronic band structure of bilayer graphene using a WSe_2 sensor layer — •Jonas Blum[1], David Tebbe[1], Takashi Taniguchi[2], Kenji Watanabe[2], Lutz Waldecker[1], Christoph Stampfer[1,3], and Bernd Beschoten[1] — [1]2nd Institute of Physics and JARA-FIT, RWTH Aachen University, Aachen, Germany — [2]National Institute for Materials Science, Namiki, Tsukuba, Japan — [3]PGI-9, Forschungszentrum Jülich, Jülich, Germany

Rydberg excitons in transition-metal dichalcogenide monolayers are highly sensitive to their dielectric environment. Previous work has shown that reflection-contrast spectroscopy provides a non-invasive optical probe of their binding energies, enabling the detection of subtle variations in the charge-carrier density n in adjacent layers of van der Waals (vdW) heterostructures. Here, we apply this technique to a fully hBN-encapsulated WSe_2/bilayer-graphene (BLG) device with graphite top and bottom gates and compare the optical response with transport measurements. By applying a displacement field D, we open a band gap in BLG. As the Fermi level is tuned from the valence band across the band gap into the conduction band, we capture changes in n through shifts in the 2s exciton binding energy. These measurements further allow us to resolve the layer population of BLG upon sign reversal of D. We also demonstrate optical quantum Hall measurements, enabling extraction of gate lever arms optically. Unlike transport measurements, this optical technique offers highly local, spatially-resolved access to the electronic band structure of BLG.

HL 3.4 Mon 10:15 POT/0081

Anisotropic Excitonic Response in $MoSe_2$-WSe_2 Lateral Heterostructures — •Miguel Morales Cocera[1,2], Franz Fischer[1,2], Carl Emil Mørch Nielsen[1], and Gabriel Bester[1] — [1]University of Hamburg, Institute of Physical Chemistry, 22761 Hamburg, Germany — [2]Max Planck Institute for the Structure and Dynamics of Matter, 22761 Hamburg, Germany

We investigate lateral heterostructures of transition-metal dichalcogenide monolayers, in particular $MoSe_2$-WSe_2. In these systems, the one-dimensional (1D) interface together with the type-II band alignment enables the emergence of 1D exciton physics within a two-dimensional monolayer material, with the "inter-layer" excitons retaining near monolayer-level brightness. Motivated by the recent experimental observation of these spatially indirect excitons [1], we calculate the exciton and trion fine structure using ab initio many-body screened configuration interaction [2]. We find that the lowest bright exciton state is non-degenerate due to the loss of symmetry induced by the 1D interface. Moreover, the many-body dipoles of these two excitons lie along different in-plane polarization axes, leading to an anisotropic optical response that may be useful for optoelectronic applications.

[1] R. Rosati, et al., Nat. Commun. 14, 2438 (2023)
[2] Mørch Nielsen, C.E., Fischer, F. & Bester, G. npj 2D Mater. Appl. 9, 11 (2025)

HL 3.5 Mon 10:30 POT/0081

Substrate interaction on local exciton/trion ratio in mono- to few-layer WS2 — •Appanna Parvangada[1,2], Dmitrii Sychev[1], and Ilka Hermes[1] — [1]Leibniz Institute of Polymer Research Dresden e.V., Dresden, Germany — [2]Institute of Applied Physics, Dresden University of Technology, Dresden, Germany

Two-dimensional Tungsten Disulfide (WS2) possesses distinctive optoelectronic properties such as high photoluminescence yield, a tunable band gap, large exciton binding, quantum confinement, strong-light matter interaction. The combination with low dimensionality makes them a favorable candidate for a variety of lightweight and flexible optoelectronic devices such as photodetectors, solar cells and LEDs.

However, large-scale industrial implementation of optoelectronic 2D materials is often impeded by their high spatial heterogeneity, caused by nanoscale variations in layer thickness, substrates interactions and local strain. Thus, standard optical characterization methods like Photoluminescence (PL) and Raman spectroscopy, which commonly provide such information, can lack the spatial resolution to resolve these variations. Here, electrical atomic force microscopy (AFM) methods with in-situ illumination at different wavelengths deliver nanoscale information on the impact of layer thickness, changes in substrates interactions and local strain onto the material's optoelectronic response.

In our study, we demonstrate the capability of photo-Kelvin probe force microscopy (pKPFM) to capture local photo-potential in mono- and few-layer WS2 and correlate PL spectroscopy. Furthermore, we investigate the impact of substrates on the local charge carriers.

HL 3.6 Mon 10:45 POT/0081

Signatures of efficient intervalley scattering by acoustic phonons in WSe2 monolayers — •Hendrik Lambers[1], Daniel Groll[2], Daniel Wigger[2], Nihit Saigal[1], Lara Blinov[1], Tilmann Kuhn[2], Alexander W. Holleitner[3], and Ursula Wurstbauer[1] — [1]Institute of Physics, University of Münster — [2]Institute of Solid State Theory, University of Münster — [3]Walter Schottky Institute, Technical University of Munich

When group VI TMDC are thinned down to the monolayer limit, their bandgap transfers from indirect to direct. While their strong exciton dominated light-matter coupling can be easily investigated by optical spectroscopy, exciton-phonon coupling is often inaccessible, even though it is important for exciton thermalization and intervalley scattering. We employ resonant Raman scattering at cryogenic temperatures to study the exciton phonon coupling in WSe_2 monolayers. In resonance with the WSe_2 exciton, we observe rich Raman spectra. Here, we focus on the resonance profiles of the degenerated A_1'/E' mode, that exhibits two asymmetric resonance peaks that cannot be described by a first order Raman scattering process. A higher-order

Raman scattering process including simultaneous generation and annihilation of acoustic M-point phonons describes the experimental resonance profile well. Our results indicate a strong electron phonon coupling and efficient intervalley scattering between the nearly degenerate direct and indirect exciton transitions in WSe_2. The findings are relevant to understand unusual bright emission in WSe_2 monolayers despite spin-forbidden lowest interband transition.

15 min. break

HL 3.7 Mon 11:15 POT/0081

Transport of exciton complexes in the presence of Fermi sea of free carriers in monolayer semiconductors — •Minushree Rout[1], Koloman Wagner[1,2], Jonas Ziegler[1,2], Raul Perea-Causin[3], Samuel Brem[4], Ermin Malic[4], and Alexey Chernikov[1] — [1]Institute of Applied Physics, Technische Universität Dresden, Germany — [2]Department of Physics, University of Regensburg, Germany — [3]Department of Physics, Stockholm University, Sweden — [4]Department of Physics, Philipps-Universität Marburg, Germany

Exciton-carrier interactions in doped monolayer semiconductors present an interesting and technologically relevant scenario in solid-state physics. Among the consequences is the formation of trions-three particle system formed when excitons bind with free charge carriers. Here, we aim to explore how trion-phonon and exciton-carrier interactions influence excitonic quasiparticle diffusion using transient microscopy. Theoretical results predict that trions have reduced mobility at low carrier densities due to strong phonon coupling and increased mass. At higher densities, effective trion diffusion should increase significantly due to the Fermi pressure effect. Previous experimental studies revealed that exciton diffusion shows a non-monotonic dependence on carrier density, transitioning from elastic scattering regime to the formation of bound quasiparticle states like trions and fermi-polarons. This work aims to uncover the fundamental mechanisms governing the transport of light-emitting quasiparticles in the presence Fermi-bose mixtures in 2D semiconductors and experimentally test the prediction of the Fermi-pressure effect.

HL 3.8 Mon 11:30 POT/0081

Investigation of dynamics and character of excitons in WSe_2 and $MoSe_2$ multilayers — •Anna Weindl[1], Matthias Brem[1], Jennifer Lehner[1], Kenji Watanabe[2], Takashi Taniguchi[3], and Christian Schüller[1] — [1]Institut für Experimentelle und Angewandte Physik, Universität Regensburg, 93053 Regensburg — [2]Research Center for Functional Materials, National Institute for Materials Science, Tsukuba Ibaraki 305-0044, Japan — [3]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba Ibaraki 305-0044, Japan

We report about our time-resolved Faraday ellipticity (TRFE) experiments on multilayers of the transition metal dichalcogenide WSe_2 and $MoSe_2$. In a continuation of our recent work by Raiber et al. [1], we aim to investigate the nature of the pseudospin oscillations that appear in the TRFE signal when we apply an in-plane magnetic field to our multilayer samples. Now we try to characterize and manipulate these oscillations by playing with different experimental parameters. Varying the angle of the magnetic field, adding an electric field or investigating the layer dependence are examples for our toolbox of parameters to gain further insights into the dynamics of the multilayers. The current results, for example on the resonance behavior of the oscillations and the layer-dependent starting point of the oscillations, will be presented.

[1] S. Raiber *et al.*, Ultrafast pseudospin quantum beats in multilayer WSe_2 and $MoSe_2$, Nat. Commun. 13, 4997 (2022).

HL 3.9 Mon 11:45 POT/0081

In-situ mapping of pressure-induced exciton traps in suspended MoS2 monolayers using Fabry-Perot interference — •Niklas Walter[1,3], Leonard Geilen[1,3], Lukas Schleicher[2,3], Alexander Musta[1,3], Anne Rodriguez[3], Benedict Brouwer[1,3], Eva Weig[2,3], and Alexander Holleitner[1,3] — [1]Walter Schottky Institute, TU Munich, Germany — [2]Chair of Nano and Quantum Sensors, TU Munich, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

We demonstrate the in-situ readout of the spatial profile of suspended MoS2 monolayers hosted on substrates with nanostructured holes. As the profiles are spatially bent, the suspended MoS2 monolayers act as exciton traps with a tunable luminescence intensity and energy. The tunability is realized by controlling the environmental pressure on the monolayers, which allows one to control hundreds of suspended MoS2 monolayers on a single substrate. The in-situ readout is based on Fabry-Perot interferences and a model of the corresponding reflectance contrast maps of the investigated monolayers.

HL 3.10 Mon 12:00 POT/0081

Coherent two-dimensional electronic spectroscopy integrated with confocal microscopy for probing 2D materials — •Trideep Kawde, Pavel Trofimov, Matteo Russo, Anton Trenczek, and Hélène Seiler — Freie Universität Berlin, 14195, Berlin, Germany

Two-dimensional electronic spectroscopy is a powerful tool for probing ultrafast processes in van der Waals materials and heterostructures. As these structures are typically only 10x100 μm in size and highly heterogeneous, the challenge of ultrafast studies on such materials is to balance requirements in spatial and angular resolutions - often requiring highly dispersive microscope objectives - with temporal resolution. We present a coherent 2D electronic spectroscopy setup integrated with a confocal back focal plane imaging setup, featuring high magnification, spatial and angle resolution, while maintaining a time resolution of ∼15 femtosecond. We demonstrate this approach on an exfoliated WSe_2 monolayer. The data reveal <100 femtosecond homogeneous linewidth broadening of the A exciton lineshape, indicating rapid exciton-energy fluctuations. These measurements provide insight into dephasing mechanisms such as excitation-induced dephasing, which sets fundamental limits to coherent control and quantum-optical applications.

HL 3.11 Mon 12:15 POT/0081

Acousto-optic characterization of van der Waals systems — •Felix Ehring, Benjamin Mayer, Hubert Krenner, Ursula Wurstbauer, and Emeline Nysten — Institute of Physics, University of Münster, Germany

With wavelengths in the micrometer range at GHz frequencies, surface acoustic waves (SAWs) are a versatile tool for radio frequency control and probing of charge carrier dynamics in novel semiconductor nanostructures. They are generated on a piezoelectric chip and routed over long distances to couple either mechanically or electrically to many solid-state nanosystems [1]. In our experiments, we fabricated hybrid lithium niobate SAW-devices in which different mechanically exfoliated transition metal dichalcogenide (TMDC) 2D materials were transferred. We investigated the influence of SAW-induced dynamic electric and strain fields on the photoluminescence (PL) of various TMDCs and their heterostructures. By combining optical and acoustic measurements, we were able to gain insights on the charge carrier dynamics and their resulting impact on exciton recombination and lifetime [2].

[1] Per Delsing et al 2019, J. Phys. D: Appl. Phys. 52 353001 [2] Emeline Nysten et al 2024, Adv Mater 36 e2402799

HL 3.12 Mon 12:30 POT/0081

Dark exciton activation in WSe_2 monolayer by tip-enhanced photoluminescence spectroscopy — Adlen Smiri, Fenda Rizky Pratama, and •Takeshi Nakanishi — MathAM-OIL AIST, Sendai, Japan

Dark excitons in 2D transition metal dichalcogenide semiconductors are characterized by long lifetimes, making them highly attractive candidates for quantum computing and optoelectronics.The purpose of this paper is to theoretically address the interactions between local electromagnetic fields and dark excitonic states, and show that the strong out-of-plane near field from a metallic tip enhances radiative recombination of spin-forbidden dark excitons by providing additional in-plane momentum to overcome momentum mismatch [1]. Using ab initio calculations, a Wannier-Mott exciton model, and a numerical solution of the Laplace equation, we model the tip-enhanced near-field and its interaction with excitons via first-order time-dependent perturbation theory. Focusing on WSe_2 monolayers, we demonstrate that the activation of dark excitons is attributed to the strong z-component of the near field induced by the tip. We also analyze substrate screening effects on excitonic properties and lifetimes. Our results offer a theoretical framework for controlled activation of dark excitons toward quantum and nanophotonic applications.

[1] Adlen Smiri, F. R. Pratama and Takeshi Nakanish, npj 2D Materials and Applications 9, 88 (2025)