CNR NANO
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UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

1-3 Sept. 2025
Modena

2D Excitonic Insulators

Ψ_k–ICSC Workshop 'Two-dimensional excitonic insulators'
1-3 September 2025, Complesso San Geminiano, Modena, Italy

Website: https://excitonic-insulator.nano.cnr.it

Following the three previous workshops that took place in 2018, 2021 and 2023, we are now organising the fourth edition of the 'Two-dimensional excitonic insulators' Series. The focus of this new edition will be the hunt for macroscopic quantum coherence, the search of new candidate materials and the prediction of experimental fingerprints of the condensed excitonic phase, the understanding of the relation between excitonic and other unconventional phases. Building on the discussion of common themes and novel challenges, both theoretical and computational, this Workshop will progress our understanding of interacting systems in low dimensions.

The organisers
Hope Bretscher (MPI Hamburg, Germany),
Elisa Molinari (UniMoRe, Modena, Italy),
Massimo Rontani (Cnr-Nano, Modena, Italy)

ICSC
Centro Nazionale di Ricerca in HPC,
Big Data and Quantum Computing

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10:00 - 10:30	**Massimo Rontani** Theory of the excitonic insulator phase and its signatures in monolayer WTe_2
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11:00 - 11:30	**Zahid Hasan** Topological excitonic insulator with tunable momentum order
11:30 - 12:00	**Steven Louie** Ab initio study of excitonic insulators: an unconventional condensate and *p*-wave spin textures in $1T'$ monolayer MoS_2
12:00 - 12:30	**Luis A. Jauregui** Manipulating topological phases and correlated states in $HfTe_5$
12:30 - 12:45	Additional Q&A and discussion
12:45 - 14:00	Lunch

Throughout the workshop:

- invited presentations are 30’ including 5’ discussion
- contributed presentations are 15’ including 3’ discussion
- additional Q&A and discussion at the end of the sessions

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15:15 - 15.30	**Leonetta Baldassarre** Advantages and challenges of resonance Raman with infrared excitation in the study of low energy excitations in 2D materials
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14:00 - 14:30	**Kamran Behnia** Field-induced excitonic insulator in graphite
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II

Abstracts

1. Investigations of the possible excitonic insulator state in neutral monolayer WTe_2

David Cobden

Department of Physics, University of Washington, Seattle, Washington 98195, USA

When WTe_2 is thinned down to a bilayer or monolayer a small charge gap develops which may well originate from interactions between electrons and holes in what would otherwise be a compensated semimetal. The resulting state (which, seemingly incidentally, is topological) has been proposed to be a two-dimensional excitonic insulator. However, the charge or spin density waves that would be expected in a standard exciton condensation picture have not been detected. I will discuss the results of several experiments investigating the electronic spectrum as a function of doping, disorder, and screening by an adjacent layer. Signatures of strong correlations are indeed present, including non-thermal broadening, negative compressibility, and suppression of the gap when the compensation is broken, but the EI paradigm will probably need to be amended or extended to properly understand the thermodynamics and transport of this unusual electronic system.

2. Theory of the excitonic insulator phase and its signatures in monolayer WTe_2

Massimo Rontani

CNR-NANO, Via Campi 213a, 41125 Modena, Italy

In this talk I will review our theoretical work on two-dimensional semimetals in the T' phase, as possible hosts of the long-sought excitonic insulator phase [1-3]. These systems are major candidates in view of the enhanced electron-hole attraction due to reduced dimensionality, as confirmed by an increasing body of evidence [2,4]. Our approach relies on the integration of first-principles and model approaches. The former provides an accurate treatment of screening, and gives full access to the exciton wave function and its energy spectrum. The latter, which builds on the ab-initio information, allows us to manage the coupled gap equations that control the stability and broken symmetry of the excitonic phase. These equations are complex, in view of the multiple degrees of freedom (spin and orbital) of excitons in monolayers, and may hardly be treated in a black-box manner.

I will specifically address the puzzle of monolayer WTe_2 [2-4], whose many-body gap is thought to be sustained by excitons with finite momentum: While a charge density wave is expected, no one is detected. I will show how this behavior is related to the giant exchange interaction experienced by the bound electron-hole pairs [3]. Eventually, I will discuss the band structure of the excitonic insulator phase, and predict how its peculiar fingerprints emerge in SdH oscillation and photoemission experiments.

Acknowledgements: This work is done together with Claudia Cardoso, Matteo D'Alessio, Daniele Varsano, Elisa Molinari, David Cobden.
We acknowledge ISCRA for awarding access to the Leonardo supercomputer, owned by the EuroHPC Joint Undertaking, hosted by CINECA, Italy.

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3. C. Cardoso *et al.*, in preparation (2025).
4. Jia *et al.*, Evidence for a monolayer excitonic insulator, Nature Physics **18,** 87 (2022).

3. Topological excitonic insulator with tunable momentum order

Zahid Hasan

Laboratory for Topological Quantum Matter and Advanced Spectroscopy, Department of Physics, Princeton University, Princeton, NJ, USA
Princeton Materials Institute, Princeton University, Princeton, NJ, USA
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

> I plan to talk about how to find correlated electron physics in topological materials including recent work just got published: **Hossain, M.S., Cheng, ZJ., Jiang, YX. et al. Topological excitonic insulator with tunable momentum order. Nat. Phys. (2025). https://doi.org/10.1038/s41567-025-02917-6**

4. Ab initio study of excitonic insulators: an unconventional condensate and p-wave spin textures in $1T'$ monolayer MoS_2

Steven G. Louie

University of California at Berkeley and Lawrence Berkeley National Lab

In this talk, we present a parameter-free ab initio methodology to compute the electron-hole pairing order parameter and single-particle excitations in excitonic insulators (EIs) within a Bardeen-Cooper-Schrieffer (BCS)-type formalism with application to monolayer molybdenum disulfide in its $1T'$ structure, a multi-band prototypical two-dimensional EI candidate. The electron-hole interaction kernel is determined from first-principles GW plus Bethe-Salpeter Equation (GW-BSE) calculations. Our results predict that, at low temperature, 1monolayer MoS_2 is in an unconventional EI phase that spontaneously breaks the inversion, rotation, and mirror symmetries of the crystal, while giving rise to odd parity and unitarity for the order parameter. We identify several telltale spectroscopic signatures emergent in this EI phase which distinguish it from the high temperature band insulator phase, exemplified with a giant **k**-dependent p-wave spin texture for the quasiparticle states. Our findings provide definitive predictions for experimental testing and reveal a new type of **k**-space spin texture from the spontaneous condensate of electron-hole pairs.

5. Manipulating Topological Phases and Correlated States in $HfTe_5$

Luis A. Jauregui

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Controlling topological phases in quantum materials offers a route to explore emergent quantum states and develop devices with topologically protected carriers. Yet, few materials allow both efficient tunability and in situ electronic measurements. Here, we present our work on $HfTe_5$, a prototypical van der Waals material with exceptional topological tunability. First, we apply a large, controllable uniaxial strain to induce a topological phase transition from a weak topological insulator (WTI) to a strong topological insulator (STI). This transition leads to a dramatic increase in resistivity of over 190,000% and results in surface-state-dominated transport at cryogenic temperatures. Second, we find that the WTI phase of $HfTe_5$ supports zeroth Landau level physics at moderate magnetic fields. Fields above 10 T drive transitions to 1D Weyl modes and, under low carrier density, stabilize a spin-triplet excitonic insulator phase, enabled by strong electronic instabilities in quasi-1D systems. Notably, in the STI phase, this excitonic phase emerges at even lower fields. Third, we explore thin $HfTe_5$ devices (<100 nm), where enhanced surface-to-bulk transport and correlated phenomena appear. These observations highlight $HfTe_5$ as a versatile platform for studying topological transitions and emergent correlated states. Together, these results position $HfTe_5$ as a key material for advancing quantum device applications, from spintronics to fault-tolerant topological quantum computing.

6. Non-reciprocal phase transitions in exciton-polariton condensates

Ron Belyansky[1], Xiaoyuan Huang[1], Ryo Hanai[2], Shuoguang Liu[3], Joseph Jachinowski[3], Cheyne Weis[3], Aashish Clerk[1], Peter Littlewood[3,4]

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Driven dissipative light-matter-coupled systems such as polariton condensates and lasers possess non- equilibrium steady states that show similarities to thermodynamically ordered phases with corresponding broken symmetries. However, as non-equilibrium dynamical systems they also can exhibit states with dynamical order (e.g. limit cycles, pattern formation) that cannot exist as ground states in a thermodynamic system. Transitions between different stationary states emerge via dynamical instabilities, and one novelty of non-equilibrium systems is the existence of transitions marked by critical exceptional points, where two (or more) collective modes merge with identical eigenvalues and eigenvectors. These states can in principle exist as steady states of a pumped system, but they are also evidenced by ultrafast probes that occur on a time scale faster than the thermalization time.

Such phenomena are generic for multicomponent non-Hermitian (and non-reciprocal) states and there is a ready classification for both classical and quantum active systems at the mean field level [1]. Beyond mean field, these transitions are described by new universality classes[2]. There is an opportunity to construct explicitly 'active' quantum matter by building non-reciprocal terms into an effective equation of motion, as in the non-reciprocal Dicke model [3] and driven quantum chains [4].

Acknowledgements: This work was supported by the Air Force Office of Scientific Research MURI program under Grant No. FA9550-19-1-0399, the Simons Foundation through a Simons Investigator award (Grant No. 669487), and was completed in part with resources provided by the University of Chicago's Research Computing Center.This research benefited from Physics Frontier Center for Living Systems funded by the National Science Foundation (PHY- 2317138). RH was supported by Grant-in-Aid for Research Activity Start-up from JSPS in Japan (No. 23K19034).

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4. R. Belyansky, C. Weis, R. Hanai, P. B. Littlewood and A. A. Clerk arXiv: 2502.05267

7. Ab initio calculations of excitons in complex 2D van der Waals Heterostructures

Kristian S. Thygesen

Technical University of Denmark (DTU), Dept. Physics

I will describe a number of recently developed computational methods to predict the optical properties of van der Waals heterostructures containing hundreds of atoms in a unit cell. To obtain the single-particle band structure, we employ a layer-projected scissors (LAPS) operator that incorporates short and long-range electron self-energy effects and ensures a proper description of the band alignment at the interface [1]. I will show that the LAPS method yields an accuracy comparable to the many-body GW approximation, but at the cost of a standard density functional theory (DFT) calculation. To compute the optical excitations, we solve the Bethe-Salpeter Equation (BSE) using a minimal basis for the electron-hole states. The screened Coulomb interaction is calculated using a mixed quantum-classical electrostatic model – an extension of the previously published QEH model. By using a hierarchical basis comprising dielectric eigenstates of the individual monolayers, we can converge the BSE calculations using only a handful of basis functions. Combining these methods, we perform a high-throughput screening to identify vdW heterobilayers with interesting excitonic properties. The calculated data is made available in the open heterostructure database HetDB [2,3], which is integrated with the C2DB monolayer database [4].

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3. M. O. Sauer et al. arXiv:2504.05754
4. https://c2db.fysik.dtu.dk

8. Efficient GW calculations for metals from an accurate ab initio polarizability

Claudia Cardoso

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Despite its success in the study of spectroscopic properties, the *GW* method presents specific methodological challenges when applied to systems with metallic screening. Here, we present an efficient and fully ab-initio implementation for the calculation of the screened potential, specifically designed for 3D and 2D metals. [1] It combines a Monte Carlo integration with an appropriate interpolation of the screened potential between the calculated grid points (W-av), complemented with an extrapolation to the long-wavelength limit, able to seamlessly account for the so-called intraband term. This method greatly accelerates the convergence of GW calculations for metals while improving their accuracy, due to the correct description of the intraband transitions in the long wavelength limit, as shown here for 3D metals and doped monolayers, such as MoS_2 and graphene. The use of W-av results in an excellent agreement with ARPES measurements for monolayer doped MoS_2. Furthermore, for graphene we show that more robust results are found with the use of higher-order Lorentzians in the description of the self-energy, together with the solution of the QP equation beyond the linearized approximation.

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9. From Dirac Altermagnets to Excitonic Spin Transport in Correlated Bilayers

Lorenzo Del Re

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Altermagnetism - a phase where antiferromagnetic order coexists with non-relativistic spin splitting - has recently emerged as a fertile ground for novel spintronic and optical functionalities. In this talk, I first present results on a two-dimensional Hubbard model that hosts interaction-driven altermagnetic states with emergent Dirac cones. Using dynamical mean-field theory, we show that strong correlations lead to a re-emergence of high-energy Dirac features near the Mott transition, even when absent in static mean-field theory. These spectral signatures produce spin-selective optical responses, including a double-peak structure and photon-energy-dependent spin activation, revealing new routes for optical manipulation of spin degrees of freedom in correlated altermagnets.

Building on this, I explore a bilayer generalization of the same model, where the inclusion of a layer degree of freedom gives rise to richer symmetry-breaking patterns that intertwine spin and interlayer coherence. In this regime, the system realizes a correlated altermagnetic phase with features akin to an interlayer excitonic insulator. I show that applying an in-plane electric field with opposite signs across the layers induces a polarisation current that drives a highly anisotropic and tunable spin current, whose sign can be reversed by varying the photon energy. This coupling between interlayer coherence and spin transport opens the door to electrically controlled spintronic responses in Mott bilayers, and highlights the role of excitonic correlations in shaping the dynamics of layered altermagnets.

10. Optical and cavity engineering of driven excitonic condensates

Denis Golež[1,2], Alexander Osterkorn[1], Yuta Murakami[3], Tatsuya Kaneko[4], Zhiyuan Sun[5], Andrew J. Millis[6,7]

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7. Center for Computational Quantum Physics, Flatiron Institute, 162 5th Avenue, New York, NY, 10010

Bilayer materials hosting interlayer excitons—comprising electrons in one layer and holes in the other—are a promising experimental platform for realising high-temperature condensates and studying their dynamical properties. Imposing a chemical potential bias through optical pumping or electrical contacts drives exciton condensates into distinct dynamical regimes. We investigate how these regimes manifest in emitted light and how they are influenced by placing the material within an optical cavity.

We show that in a bilayer system where the charge can tunnel between the layers, the chemical potential bias means that an exciton condensate is in the dynamical regime of the Josephson effect. By increasing the bias voltage, the system undergoes a transition from the phase- trapped to phase-delocalized dynamical condensation. Optical spectroscopy can identify these phases, with a strong response to weak fields near the transition due to the instability in the order parameter dynamics [1].

If such a system is placed in an optical cavity within the phase-trapped regime, coupling to photons favours a superradiant state. The phenomenon allows the device to convert DC currents into coherent photons at tunable frequencies determined by the bias and material thickness. These findings highlight mechanisms to control and harness excitonic condensates for optoelectronic applications [2].

References:

1. Alexander Osterkorn, Yuta Murakami, Tatsuya Kaneko, Zhiyuan Sun, Andrew J Millis, Denis Golež, arXiv:2410.22116.
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11. Non-equilibrium phases and phase transitions in dynamical exciton condensates

Andrew Millis

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Center for Computational Quantum Physics, Flatiron Institute, New York 10010, USA

Bilayer materials may support interlayer excitons; in experiments, a nonzero exciton density is typically sustained by a bias chemical potential. If charge can tunnel between the layers, the chemical potential bias means that an exciton condensate is in the dynamical regime of ac Josephson effect. We use a microscopic Keldysh non equilibrium field theory description and effective field theories to derive physical consequences including tunneling currents, experimental tenability of condensate from bright (emitting coherent photons) to dark condensates knobs and coupling to modes in optical cavity which may enable the realization of easily tunable super radiant phases. Connections to the theory of non equilibrium phase transitions are drawn.

Acknowledgements: This work is done in collaboration with Zhiyuan Sun, Yongin Zeng, Yuta Murukami, Tatsuya Kaneko, Valentin Crepel and Denis Golez, is published in part in PRL 132 266001 and PRL 133 217002 and is supported in part by Programmable Quantum Materials, an Energy Frontiers Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), under Award No. DE-SC0019443.

12. THz collective modes and self-cavity effects in vdW heterostructures

Hope M. Bretscher

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Columbia University, New York City, USA

Van der Waals (vdW) heterostructures exhibit a wide range of exotic many-body quantum phenomena that can be tuned in situ using electrostatic gates. The typical energy scales of many insulating gaps and collective modes fall in the few meV or THz frequency range. In this talk, I will discuss how vdW heterostructures naturally form sub-wavelength cavities due to their micron-size, confining low-energy light into the near field. I will introduce time-domain on-chip THz spectroscopy as a technique to capture the cavity electrodynamics, probing the response of vdW heterostructures to light on their natural frequency scales. This technique overcomes the mismatch between free-space THz wavelengths ($\sim$300 μm) and sample size ($\sim$10 μm) by measuring the optical conductivity on-chip, in the near field, and at finite momenta. I will illustrate how this technique can be used to both sense and control the low-energy responses of gate-tunable devices. This provides a route to capture signatures of collective modes of excitonic insulating materials such as WTe_2.

13. Counterflow excitonic plasmons on a chip

Marios H. Michael

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A defining feature of exciton condensates is the emergence of a Goldstone mode associated with spontaneous interlayer phase coherence, which enables dissipationless counterflow of electrons and holes—analogous to superfluidity in a Bose-Einstein condensate (BEC). In BECs, such superfluid behavior results from the spontaneous breaking of a continuous symmetry (typically global U(1) charge conservation). In contrast, in excitonic insulators, this symmetry is often explicitly broken by coupling to the lattice, leading to a gapped pseudo-Goldstone mode and frequently accompanied by lattice distortions. This complicates both the identification of a true excitonic condensate and the interpretation of spectroscopic signatures. Moreover, the pseudo-Goldstone mode is optically silent in the far field, making its detection especially challenging.

In this talk I will present a theoretical framework demonstrating that on-chip terahertz (THz) spectroscopy provides a direct and linear probe of the pseudo-Goldstone mode in two-dimensional excitonic insulators. This mode—referred to here as a counterflow excitonic plasmon—involves in-phase oscillations of electrons and holes. Although these oscillations produce no net dipole moment and thus evade far-field optical detection, they can couple efficiently to near-field THz pulses guided along on-chip metallic transmission lines. I will show how this coupling enables the excitation and detection of counterflow excitonic plasmons, and discuss the potential of this technique to address long standing questions in this field.

14. Electromagnetic responses of Excitonic Insulators

Yuelin Shao and Xi Dai

Department of Physics, The Hongkong University of Science and Technology, Clear Water Bay, Kowloon 999077, Hong Kong, China

In this seminar, I will first introduce the main concepts of bilayer exciton insulator, a new type of charge neutral quantum liquid recently realized in 2D materials. Then I will mostly focus on the electromagnetic responses of bilayer excitonic insulators (EIs) and identify two distinct collective modes: (1) Two gapped plasmon modes couple to the layer symmetric gauge field. The transverse mode is nearly dispersionless in the long wavelength limit, while the longitudinal mode, accounting for total charge fluctuations, has a linear dispersion with velocity proportional to 2D electrical polarizability. (2) A gapless phase (Goldstone) mode and a gapped amplitude mode, associated with the fluctuations of EI order parameter, couple to the layer antisymmetric gauge field. In the long wavelength and low frequency limit, the phase mode behaves like an acoustic phonon with speed inversely proportional to the square root of exciton compressibility. Significantly, its linear dispersion yields a cubic frequency dependence of the real admittance in microwave impedance microscopy (MIM), providing a method to detect the Goldstone mode directly.

15. A new Gross-Pitaevskii approach for exciton superfluids and incompressible supersolids

Sara Conti[1], David Neilson[1], Andrey Chaves[2], Luis A. Pena Ardila[3], and Milorad Milosevic[1]

1. University of Antwerp, Antwerp, Belgium
2. Universitade Federal do Ceara, Fortaleza, Brasil
3. Università di Trieste, Trieste, Italy

Recent reports of signatures of superfluidity [1,2,3] of dipolar excitons have drawn a lot of attention to excitonic bilayer semiconductor systems in which electrons and holes are confined in separate layers. In a variational calculation we have predicted a transition to an incompressible supersolid with one exciton per site in an experimentally accessible region of phase space [4].

We investigate the superfluid and supersolid ground states with a time-dependent Gross-Pitaevskii approach for the 2D dipolar excitonic system. In this system, the interaction between the excitons is purely repulsive long-range dipole-dipole. This contrasts with ultracold dipolar gases [5], where the effective interaction contains attractive as well as repulsive parts. We construct a new Gross-Pitaevskii formalism (i) to exclude the self-interaction energies of excitons on single occupancy sites, and (ii) to take into account strong two-particle correlations. The Gross-Pitaevskii equation at T=0 is solved over a range of experimentally accessible values of the parameters: layer separation and exciton density. The solutions include both a superfluid and an incompressible supersolid ground state.

We further investigate formation of vortices in the exciton superfluid. In neutral superfluids, stabilization and observation of vortex matter is used to decisively establish the existence coherent condensation [6] and to characterize a superfluid to supersolid transition [7]. We provide a description characteristics, interaction, and lattices of the vortices, while tuning the exciton dipole moments and the exciton density.

An interesting picture emerges since a density pileup and saturation of the vortex core size occur at the superfluid-to-supersolid transition. At the transition, the vortices are sufficiently compact to fully fit within single unit cells of the incompressible supersolid.

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16. Indirect excitons

Leonid Butov

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Spatially indirect excitons (IXs), also known as interlayer excitons, are formed by electrons and holes in separated layers in a heterostructure (HS). Due to the layer separation, the IX lifetimes are orders of magnitude longer than lifetimes of spatially direct excitons. The long lifetimes allow IXs to cool below the temperature of quantum degeneracy and form quantum bosonic states. We present recent results in quantum IX systems. In GaAs HS: Cooper-pair-like excitons [1], excitonic Bose polarons [2], and the Mott transition in excitonic Bose polarons [3]. In van der Waals HS: long-distance IX transport [4], IX mediated long- distance spin transport [5], and efficient IX transport with anomalously high diffusivity, orders of magnitude higher than for regular diffusive exciton transport in van der Waals heterostructures, agreeing with long-range ballistic transport [6].

Acknowledgements: The PL and PLE studies were supported by DOE Award DE-FG02-07ER46449, the device fabrication by NSF Grant 1905478, the GaAs heterostructure growth by Gordon and Betty Moore Foundation Grant GBMF9615 and NSF Grant DMR 2011750.

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17. Many-body physics and Excitons: two kinds of Mott transitions, two kinds of interactions

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We briefly review two collective many-body phenomena involving excitons and strong interparticle correlations: (1) The exciton Mott transition in photoexcited semiconductors and (2) the effects of a Mott transition on excitonic condensation in an electron-hole bilayer with short-range interactions. In the first case we address the transition from an exciton gas to an electron-hole liquid in an idealized model for a photoexcited semiconductor and we show a rich phase diagram, in which the transition changes from continuous to discontinuous as a function of the exciton binding energy, and different kinds of phase separation are obtained [1].

For the second systems we consider a two-layer Hubbard model. Here we have a strong intra-layer repulsion inducing strong correlations, while the inter-layer interaction can lead to exciton formation and condensation. We demonstate that the proximity to the in-layer Mott transitions favours inter-layer exciton condensation. The mechanism relies on the onset of inter-layer spin-spin correlations when the electrons and holes in the two layers approach Mott localizations and turn into localized spins. [2].We finally touch upon the role of electron-phonon coupling in exciton condensation in two-layer systems, demonstrating a non-trivial role of the dynamical nature of the phonons (measured by the phonon frequency) in favouring or disfavouring the exciton condensation and we discuss the competition between phonons and the Hund's exchange coupling [3].

Acknowledgements: This work is supported by National Recovery and Resilience Plan (PNRR) MUR Project No. CN00000013-ICSC and PE0000023-NQSTI and by MUR via PRIN 2020 (Prot. 2020JLZ52N 002) programs, PRIN 2022 (Prot. 20228YCYY7).

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18. Light-Induced Electron Pairing in Laser-Excited Semiconductor-Metal Heterostructures

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Laser excited quasi-2D heterostructures of transition metal dichalcogenides (TMDCs) have been shown to allow for quite a few higher order excitonic bound states such as trions (charged excitons), biexcitons (excitonic molecules), charged biexcitons, and more [1-5]. Such a large variety of coupled electron-hole quasiparticle excitations opens the door to a variety of new laser- driven phenomena in these systems, including metal-insulator transitions and Wigner crystallization, Bose-Einstein condensation (BEC), and even unconventional superconductivity [6-10]. Recently [5,10], an atom-like excitonic complex was reported experimentally in laser excited bilayer TMDCs in accord with theory predictions – the quaternion, the tightly bound complex of a free charge carrier in the top layer coupled to a like-charge trion in the bottom layer – provided that the entire heterostructure is placed close to a metallic surface to screen the excessive repulsive interaction in the system. Since such quaternions carry two net charges and are also bosonic, BEC of these quasiparticles would be a superfluid and therefore also a Schafroth superconductor [11]. Here, we develop a theoretical framework to explain the latest experimental observations of the Zeeman effect for quaternion complexes in perpendicular magnetostatic field [10]. Our theory is based on group theoretical analysis and spin-Hamiltonian formalism. We show that, contrary to the linear Zeeman shift known for excitons and trions in TMDC monolayers [12], the quaternion ground state is the spin-triplet to exhibit a *quadratic* magnetic field shift similar to that known for hydrogen-like atoms (whose ground state is singlet). In addition to prospective laser-driven BEC and superconductivity, another fascinating possibility for quaternions is that, as these bound four- particle doubly charged complexes repel each other, they could form a bosonic Wigner crystal. Such a light-induced quasiparticle crystal would be an *atom-like* supersolid inside of the crystalline material. The process of Wigner crystallization is controlled by the ratio of the Coulomb repulsion energy to the average single-particle kinetic energy of a statistical ensemble of charge carriers [13,14]. Due to the double charge and quadruple mass as compared to electrons, this ratio is at least 10 times greater for quaternions, suggesting higher crystallization temperature than that of the order of 10 K reported for quasi-2D electrons in TMDC nanostructures [15].

Acknowledgements: This research is supported by the U.S. Army Research Office grant No. W911NF-24-1-0237.

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19. Advantages and challenges of resonance Raman with infrared excitation in the study of low energy excitations in 2D materials

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Raman spectroscopy is a key asset to study the electronic and vibrational properties of graphene and other two-dimensional materials that display Raman spectra composed of first order modes together with narrow second-order double resonant modes arising from intervalley or intravalley scattering. Notably, for resonant processes, by changing the excitation laser energy different regions of the electron and phonon dispersions can be probed [1,2]. In this presentation I will discuss our experimental approach to study the competing low-energy interactions in these systems by lowering the excitation energy and leveraging on Raman processes resonant with electronic states in the infrared. I will provide an overview of the development of the experimental setup, together with results on $MoSe_2$ [3] and $MoTe_2$. As further example of the potential of this experimental approach, I will discuss our results on graphene where close to the Dirac point at K we find a giant increase of the intensity ratio between the double-resonant 2D and 2D' peaks. By comparing to ab-initio calculations, we explain our experimental observation by an enhanced, momentum-dependent electron-phonon coupling between electrons and zone-boundary optical phonons [4,5]. The modification of electron-phonon coupling is then studied as a function of dimensionality and doping.

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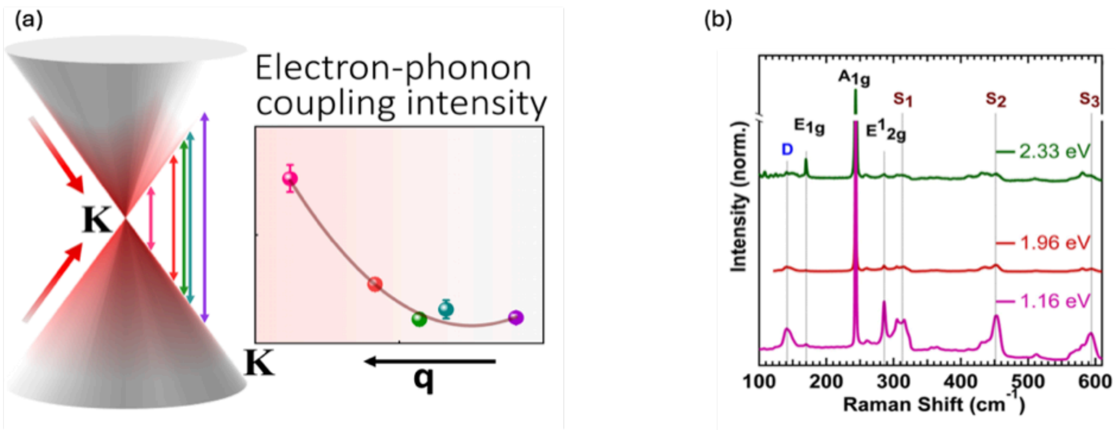

Figure 19.1: (a) Sketch of the different excitation processes in graphene when reducing the excitation laser energy allowing to move towards the Dirac point. By lowering the energy of the excitation we find an enhancement of the electron-phonon coupling while approaching K. (b) Raman spectra of $MoSe_2$ measured with excitation energies down to the infrared, where a strong resonant enhancement of second order modes is found.

20. Excitonic states and their fingerprints on electronic structure

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Excitons, bound states of electrons and holes, are fundamental quasiparticles induced by coherent light–matter interactions. Time and angle resolved photoemission spectroscopy has been recently shown to be a powerful tool to reveal exciton formation in the single particle spectral function, opening up the exciting frontier to study momentum dependent exciton driven band structure renormalization, and ultimately search distinctive signature of exciton condensation in the band structure. Here I will discuss our recent work utilizing XUV and UV time resolved ARPES to study exciton formation in real time. I will show how their formation can uniquely modify the band structure in a k dependent way and will reveal under which conditions these excitonic state can be driven in the presence of topological invariants, what properties of the topological state persists and what are their fingerprints in the material's band structure. The potential of driving excitonic condensation in these topological states is also discussed.

21. Green's function zeros in Mott quantum magnets

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Even deep in strongly correlated Mott insulating phases, the free, non-interacting energy-momentum relation plays a crucial role for the analytic structure of the single- particle Green's function G [1]. In particular, the momentum structure of the zero eigenvalues of G is given by an appropriately renormalized form of the bare electronic dispersion, despite the presence of a hard gap which prevents from a straightforward spectroscopic access. After exploring topological classification schemes based on Green's function zeros and their connection with low-energy excitations in spin liquids [2], I will present setups that have been put forward for an experimental detection [3,4]. In the second part of the talk, I will extend the notion of zeros of G to long-range ordered magnetic phases [5] and discuss the role of temperature. If time allows, I will discuss other types of symmetry breaking and connect to altermagnets with interlayer excitonic order [6].

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22. On the possibility of BEC of two dimensional interlayer excitons

Ataç İmamoğlu

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It is widely assumed that Mermin-Wagner theorem prohibits true Bose-Einstein condensation of two dimensional excitons, and upon cooling the system would undergo a BKT transition to a superfluid state. Here, we discuss whether long-range electron-hole exchange interaction could induce true off-diagonal long-range order in this system.

23. Superconductivity in high-mobility monolayer WTe_2

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The monolayer excitonic insulator candidate WTe2 undergoes a transition to a gate-tunable superconducting state when electron-doped above a low threshold density [1,2]. It has been speculated that the superconductivity is unconventional, topological, and/or influenced by excitons. We have recently employed a horizontal-flux crystal growth technique [3] that produces WTe_2 crystals with several times higher mobility than before, exhibiting record magnetoresistance. In the highest quality samples we find that the threshold doping is as low as 1012 cm^{-2} and the superconductivity shows a dome with a maximum T_c approaching 1.8 K. However, in other samples the threshold doping is higher and T_c several times lower. This strong sensitivity to disorder is indicative of non-s-wave pairing. Neverthless, and although the Fermi surface is small, the cleanest samples appear to be in the weak coupling regime, and the dependence of the coherence length on is consistent with BCS theory in the clean limit. We also look at the possibility of an intervening metallic state at the insulator-superconductor quantum phase transition, which has been shown signs of unconventional nature [4]. Finally, we consider the possibility that the unusual form of the superconducting dome is connected to proximity to a condensate of excitons or biexcitons.

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24. Stabilization of sliding ferroelectricity through exciton condensation

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Bilayer WTe_2 is the first example of a sliding ferroelectric semimetal. Its polarization can be switched by an applied electric field even at high temperatures [1] and it was shown that the switching co-occurs with interlayer sliding [2]. However DFT-based calculations predict the energy barrier of the sliding process to be a fraction of a meV, which is not compatible with the high experimental Curie temperature of the ferroelectric switching. Here we move from the recent evidence of important excitonic effects in mono- and bi-layer WTe_2, leading to a ground-state excitonic insulator phase [3], and analyze the role that electron-hole interaction can play in the ferroelectric properties of bilayer WTe_2. We find that the bilayer can undergo a transition to an excitonic phase where the renormalization of the bands accounts for the energy cost of exciton ionization. This opens a gap in the band structure, thus changing the energy of the system and in turn the energy barrier for the sliding process, showing that excitonic effects can contribute to the energetics of the ferroelectric switching and help recover a theoretical understanding of the experimental evidence.

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25. Unconventional excitonic insulators in two-dimensional topological materials

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We theoretically studied the excitonic insulator in a pair of recently proposed two-dimensional candidate materials with nontrivial band topology. Contrary to previous works, we included interaction channels that violate the individual electron and hole number conservations. These are on equal footing with the number-conserving processes due to the substantial overlap of Wannier orbitals of different bands, which cannot be exponentially localized due to the nontrivial Chern numbers of the latter. Their inclusion is crucial to determine the symmetry of the electron-hole pairing and, by performing mean-field calculations at nonzero temperatures, we found that the order parameter in these systems is a chiral d-wave. In this talk I will discuss the nontrivial topology of this unconventional state as well as some properties of the associated Berezinskii-Kosterlitz-Thouless transition. In particular, I will argue that here it becomes a smooth crossover, for which we estimated an associated temperature lying between 50 and 75 K on realistic substrates. This is over an order of magnitude larger than in the number-conserving approximation where s-wave pairing is favored. I will also propose an experimental setup which leverages the topological properties to indirectly probe the presence of this phase. Our results highlight the interplay between topology at the single-particle level and long-range interactions, motivating further research in systems where both phenomena coexist.

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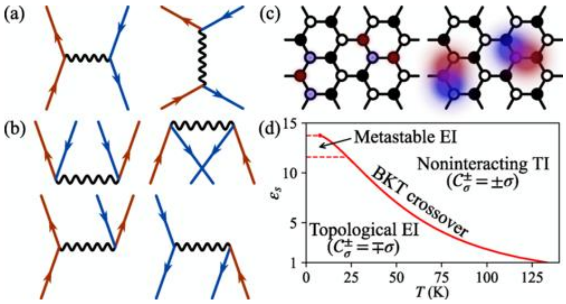

Figure 25.1: (a) U(1)-conserving channels; the number of electrons (red) is the same before and after the scattering, and equally for the holes (blue). (b) Examples of U(1)-breaking channels, where the individual numbers of electrons and holes is not conserved after the scattering process. (c) Sketch of Wannier orbitals of trivial bands (left) and bands with a nonzero Chern number (right). Due to the nonlocalizability of the latter, orbitals corresponding to conduction and valence bands have significant overlaps in coordinate space and the processes depicted in (b) become relevant. (d) Phase diagram of one of the proposed materials as a function of the temperature and the dielectric constant of the substrate.

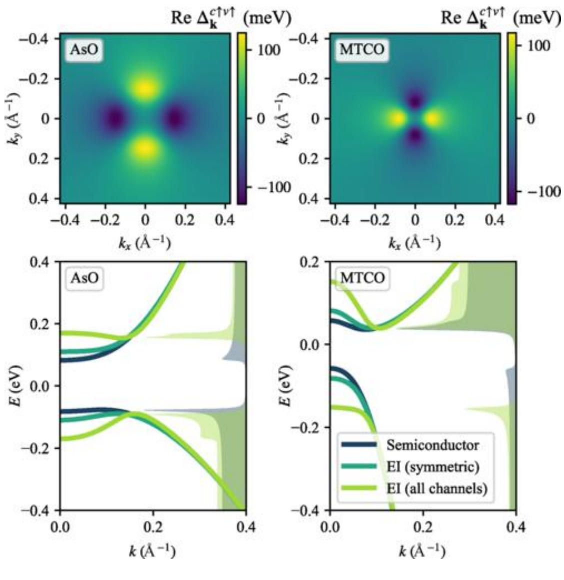

Figure 25.2: Real part of the excitonic gap function (top) and quasiparticle dispersions (bottom) for both materials. We compare the dispersions in the presence of all channels and of U(1)-symmetric processes only. In the former case, the quasiparticle gap is inverted with respect to the bare bands in the absence of an excitonic insulator. The right side of the plots show the density-of-states profiles of the underlying topological insulator and of our d+id excitonic insulator in arbitrary units.

26. Magnetic tuning of coupled excitonic-structural transitions

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The search for excitonic coherence in quantum materials is hindered by the fact that excitonic orders often couples to other types of symmetry breaking. The candidate material Ta_2NiSe_5 represents a paradigmatic example in which the excitonic order parameter couples linear with structural distortion giving rise to a structural distortion whose origin stimulated an intense debate in recent years [1,2]. In this seminar, I will discuss strategies for tuning coupled excitonic-structural transitions by exploiting time-reversal symmetry breaking realizations of the excitonic instability. I will introduce the general mechanism for a toy model [3]. Eventually, I will show the explicit application in the case of Ta_2NiSe_5 in perpendicular field [4].

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27. Binding and spontaneous condensation of excitons in narrow-gap carbon nanotubes

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Ultraclean, undoped carbon nanotubes are always insulating, even when the gap predicted by band theory is zero. The residual, observed gap is thought to have a many-body origin. Here we theoretically show that the correlated insulator is excitonic, extending our previous claim, limited to gapless (armchair) tubes [1], to all narrow-gap tubes, irrespective of their size. By enhancing the two-band model with an accurate treatment of screening, validated from first principles, we derive the scaling law of the exciton binding energy with the tube radius and chirality, and compute self-consistently the fundamental transport gap of the excitonic insulator. Our findings point to the broader connection between the exciton length scale, dictated by structure, and the stability of the excitonic phase. [2]

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28. Field-induced excitonic insulator in graphite

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In graphite, electrons and holes are confined to their lowest Landau levels when magnetic field exceeds 10 T. Between 22 T and 70 T, two insulating states emerge, with critical temperatures each displaying a distinct dome-like field dependence [1]. The summit of the first dome corresponds to a critical temperature of 9.2 K and a critical magnetic field of 47 T. At this critical field, hole and electron Landau sub-bands simultaneously cross the Fermi level allowing exciton formation with infintesimal Coulomb attraction. Quantifying the effective mass and the spatial separation of the excitons in the basal plane, we found that the expected degeneracy temperature of the excitonic fluid is close to the experimentally measured critical temperature. This supports the picture of a metal-insulator transition driven by the Bose-Einstein Condensation (BEC) of excitons [2]. The evolution of this dome under hydrostatic pressure documents an original case of BCS-BEC crossover, which is tunable by both magnetic field and pressure, but its summit remains locked at a fixed temperature [3].

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29. Signatures of Collective Ordering and Ferroelectric Phases of Moiré Excitons

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In this talk, I will present our recent observation of many-body interaction-induced ferroelectric ordering of moiré excitons in H-stacked WSe_2/WS_2 heterobilayer. Strong exciton-exciton repulsion leads to an excitonic Mott state with a large on-site energy $U_{xx} \sim 35$ meV. Due to the interplay of anisotropic nature of dipolar interactions, large U_{xx}, and spatially indirect in-plane excitons in H-stacking, we observe signatures of ferroelectric ordering of moiré excitons in time-resolved photoluminescence spectra. In particular, we find a reduction in emission lifetime consistent with this ordering, which can be thought of as a novel cooperative phenomenon. Our observations open new avenues to explore a system of correlated moiré electrons and excitons as a rich platform to study and create quantum matter in a driven-dissipative setting and also a many-body quantum open system simulator to uncover novel cooperative phenomena.

30. Control of phonon modes through the collective modes in excitonic insulators

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Electron-hole bound pairs, interacting by Coulomb force, are common excitations in semiconductors. Spontaneous condensation of excitons is expected to occur if the binding energy of the excitons overcomes the small band gap of the semiconductor, giving rise to a new insulating ground state, the so-called excitonic insulator (EI). The excitonic condensate is not directly observable in EI candidates. However, the phonon excitations couple to the electrons in such a way that may affect the excitonic condensate. For instance, a strong Raman anomaly has been observed for the EI candidate, Ta_2NiSe_5, across the transition[1, 2]. In this work we aim at theoretically studying the phonon modes screened by the excitonic order parameter fluctuations. We show the excitonic condensate play an important role in renormalizing the phonon spectral densities. Using the dressed phonon Green's functions, we could map out some regions in the MF phase diagram where the phonon modes spectral density behave different. More importantly, we found that phonon mode becomes soft in the band insulator phase and disappear by falling into the zero energy at strong electron-phonon couplings. While it exist as a hybridized mode, as an effect of the EI phase mode, in the EI phase at even strong electron-phonon couplings. Our calculated results will help elucidate the origin of the phase transitions in EI candidates with strong elecron-phonon coupling.

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