BOOK OF ABSTRACTS

FLEET EU International Conference 2023

Transport in exciton condensates and exciton insulators

University of Camerino Campus
in San Benedetto del Tronto
September 11, 2023

More details about the conference can be found at:
`http://www.multisuper.org/fleet-conference-2023`

Invited Speakers

- Stefania De Palo, CNR-IOM, Trieste, Italy
- Dmitry Efimkin, Monash University, Australia (online talk)
- Michael Fuhrer, Monash University, Australia
- Alexander Hamilton, University of New South Wales (UNSW), Sydney, Australia
- Oleh Klochan, University of New South Wales (UNSW), Sydney, Australia
- Zeb Krix, University of New South Wales (UNSW), Sydney, Australia
- David Neilson, University of Antwerp, Belgium
- Fredrik Nilsson, Technical University of Denmark
- Filippo Pascucci, University of Antwerp, Belgium and University of Camerino, Italy
- Andrea Perali, University of Camerino
- Massimo Rontani, CNR-NANO, Italy
- Gaetano Senatore, University of Trieste, Italy
- Jie Shan, Cornell University, USA (online talk)

About

Topics

- Electron-hole superfluidity in van der Waals heterostructures and semiconducting double quantum wells.
- Exciton polaritons. Excitons in moirè superlattices.
- Quest for supersolidity with exciton condensates.
- Spatially indirect excitonic condensation and exciton insulators.
- Transport and collective phenomena in exciton condensates.
- Ultracold atoms: perspectives and first experiments.

Organizing committee

Sara Conti (Antwerp); Stefania De Palo (CNR, Trieste); Alexander Hamilton (UNSW, Sydney)
Milorad V. Milosevic (Antwerp); David Neilson (Antwerp) (Chair); Andrea Perali (Camerino) (Chair)

Local organizers

Luis A. Peña Ardila, Andrea Perali, University of Camerino ,Italy
David Neilson, University of Antwerp, Belgium

Timetable

CT=invited talk

Monday– September 11

8:30–9:00	**Registration and Opening**		
09:00–09:30	CT	**Michael Fuhrer**	P-type Ohmic contact to a monolayer TMD semiconductor – towards indirect exciton devices
09:30–10:00	CT	**Fredrik Nilsson**	Exciton superfluidity in van der Waal heterostructures: Material specific screening from first principles
10:00-10:30	CT	**Alexander Hamilton**	The Hunt for the Equilibrium Indirect Exciton Superfluid
10:30–11:00	CT	**David Neilson**	Chester Supersolid of Spatially Indirect Excitons in Double-Layer Semiconductor Heterostructures
11:00–11:30	**Coffee Break**		
11:30-12:00	CT	**Dmitry Efimkin**	The fluctuational internal Josephson and the Coulomb drag-like effects in electron-hole bilayers
12:00-12:30	CT	**Gaetano Senatore**	Excitations in symmetric electron-hole bilayer: quasiparticle energies, collective excitations
12:30-13:00	CT	**Massimo Rontani**	Monolayer WTe2 and pressurized MoS2 as ideal excitonic insulators
13:00–14:30	**Lunch Break**		
14:30–15:00	CT	**Stefania De Palo**	Excitonic condensation in an electron-hole bilayer: a Quantum Monte Carlo study
15:00–15:30	CT	**Oleh Klochan**	Making artificial electronic crystals
15:30–16:00	CT	**Andrea Perali**	BCS-BEC crossover in electron-hole double layer superfluids
16:00–16:30	**Coffee Break**		
16:30–17:00	CT	**Jie Shan**	Excitonic insulator in atomic double layers: an experimental realization
17:00–17:30	CT	**Zeb Krix**	Artificial crystals using bilayer graphene: A new platform for engineering strongly correlated effects
17:30–18:00	CT	**Filippo Pascucci**	Josephson effect and superfluidity in electron-hole bilayer heterostructures
18:00–18:15	**Closing remarks**		

List of Abstracts – Talks

Talks (Alphabetic order)

Excitonic condensation in an electron-hole bilayer: a Quantum Monte Carlo study

Stefania De Palo
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[2] *Dipartimento di Fisica, Universita‘ di Trieste,Trieste, Italy*

Using Quantum Monte Carlo simulations we map the phase diagram of a symmetric electron-hole bilayer; a minimal model where we include one of the structural key features of coupled graphene bilayers separated by a thin insulating materials: the valley degeneracy. We found an excitonic phase (bound pairs of opposite charges) sandwiched between a plasma phase and a quadriexcitonic phase (characterised by complexes of eight-particles). The signatures of excitonic condensation are found only in the intermediate excitonic phase density window. This result is consistent with a finite tunnelling conductivity, interpreted as signature of condensation, experimentally observed only between two finite values of carrier density in graphene bilayers. We also studied the properties of the isolated excitonic complexes, in particular we focus on the stability of the isolated quadriexciton with respect to the dissociation into two biexcitons.

The fluctuational internal Josephson and the Coulomb drag-like effects in electron-hole bilayers

Dmitry K. Efimkin
School of Physics and Astronomy, Monash University, Victoria 3800, Australia ARC Centre of Excellence in Future Low-Energy Electronics Technologies, Monash University, Victoria 3800, Australia

Part 1: Tunneling and fluctuating electron-hole Cooper pairs in double bilayer graphene A strong low-temperature enhancement of the tunneling conductance between graphene bilayers has been reported recently and interpreted as a signature of equilibrium electron-hole pairing, first predicted in bilayers more than 40 years ago but previously unobserved. Here we provide a detailed theory of conductance enhanced by fluctuating electron-hole Cooper pairs, which are a precursor to equilibrium pairing, that accounts for specific details of the multiband double graphene bilayer system which supports several different pairing channels. Above the equilibrium condensation temperature, pairs have finite temporal coherence and do not support dissipationdess tunneling. Instead they strongly boost the tunneling conductivity via a fluctuational internal Josephson effect. Our theory makes predictions for the dependence of the zero bias peak in the differential tunneling conductance on temperature and electron-hole density imbalance that capture important aspects of the experimental observations. In our interpretation of the observations, cleaner samples with longer disorder scattering times would condense at temperatures Tc up to $\sim 50\,\mathrm{K}$, compared to the record $\mathrm{Tc} \sim 1.5\,\mathrm{K}$ achieved to date in experiment. [1].
Part 2: Anomalous drag in electron-hole condensates with granulated order We explain the strong interlayer drag resistance observed at low temperatures in bilayer electronhole systems in terms of an interplay between local electron-hole-pair condensation and disorderinduced carrier density variations. Smooth disorder drives the condensate into a granulated phase in which interlayer coherence is established only in well-separated and disconnected regions, or grains, within which the densities of electrons and holes accidentally match. The drag resistance is then dominated by Andreev-like scattering of charge carriers between layers at the grains that transfers momentum between layers. We show that this scenario can account for the observed dependence of the drag resistivity on temperature and, on average, charge imbalance between layers. [2].

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P-type Ohmic contact to a monolayer transition metal dichalcogenide semiconductor – towards indirect exciton devices

Michael Fuhrer
[1] *School of Physics and Astronomy, Monash University, Melbourne, 3800, Australia*
, [2] *ARC Centre for Future Low Energy Electronics Technologies, Monash University, Clayton, Victoria 3800, Australia*

Double layers of atomically thin semiconducting transition metal dichalcogenides (TMDs) afford a platform for condensation of spatially indirect excitons, and signatures of exciton condensation have been seen in photoluminescence as well as capacitive compressibility measurements. Separate electrical contacts to the electron and hole layers enables superfluid counterflow and can realize ultra-low energy electronic switches based on exciton condensation, however Ohmic electrical contacts to p-type TMDs have been challenging. Here, we present low-temperature p-type Ohmic contact to $1\,\mathrm{L}-\mathrm{WSe}_2$ field-effect transistors at carrier densities (n) below $n=1\times10^{12}\,\mathrm{cm}^{-2}$ [1]. Monolayer WSe_2 was sandwiched by hexagonal boron nitride flakes by a dry transfer technique and electrically contacted with $20\,\mathrm{nm}$ thick amorphous MoO_3 followed by Pd metal. The Ohmic nature of the contact is supported by linear current-voltage characteristics down to a temperature of $10\,\mathrm{K}$ and carrier densities from $n=7.7\times10^{11}\,\mathrm{cm}^{-2}$ to below the threshold, temperature-independent output curves up to room temperature, and negligible contact barrier down to subthreshold regime. Furthermore, the contact resistivity of MoO_3-contacted $1\,\mathrm{L}-\mathrm{WSe}_2$ FET is $30.2-64.8\mathrm{k}\Omega\cdot\mu\mathrm{m}$ at $n=1.5\times10^{12}\,\mathrm{cm}^{-2}$, which is the lowest reported for 1LWSe_2 FETs at such low carrier density.

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The Hunt For The Equilibrium Indirect Exciton Superfluid

Alexander Hamilton
University of New South Wales, Sydney, Australia

It has long been known that the attractive Coulomb interaction between electrons and holes confined to separate 2D layers can support exotic superfluid and insulating states [1,2]. Over the past half century there has been extensive efforts in a variety of material systems to realise these superfluid and strongly correlated states. In this talk I will review the experimental challenges in realising the equilibrium electron-hole condensate in conventional semiconductors, and the new opportunities opened up by van der Waals materials [3,4].

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Making artificial electronic crystals

[1,4] Oleh Klochan, [1] **Daisy Wang,**[1] **Zeb Krix,** [1] **Oleg Sushkov,** [2,3] **Ian Farrer,** [2] **David Ritchie,** [1] **Alex Hamilton.**
[1] *School of Physics, UNSW Sydney,* [2] *Cavendish Laboratory, Cambridge University,* [3] *Department of Electronic and Electrical Engineering, Sheffield University, and* [4] *School of Science, UNSW Canberra*

The electronic properties of materials are determined by the atomic constituents and their crystal lattice structure. Engineered electronic materials, which are created by applying a designed spatially periodic potential, a superlattice, have offered a powerful way to alter the properties of natural crystals in a controlled manner. For example, Moire superlattices, where different layers of two-dimensional (2D) materials are stacked and twisted to create a superlattice modulation potential, are currently attracting significant attention as they provide an ideal platform for both studying fundamental physics as well as promising future applications. Imposing spatially periodic electric field via nanolithography has also been proven to be a powerful technique to create a superlattice. It offers an excellent control of the lattice parameters and can be easily integrated into many existing device architectures, e.g. a semiconductor FET, which has an advantage of well-established fabrication technology and superb device quality. Using this approach, we demonstrate a versatile device architecture that allows independent control of carrier density and potential modulation across a wide range. In the weak modulation regime, we observe formation of artificial Fermi surfaces via quantum oscillations in the magnetoresistance. In the strong modulation regime, we detect the artificial mini bands via the low field Hall effect. Hall resistance shows multiple transitions from electron-like to hole-like behaviour as the chemical potential is swept through the different artificial bands, consistent with our band structure calculations. We are able to continuously tune the artificial bandstructure from free electrons to those of electrons in graphene-like and eventually Kagome-like bands.

Artificial crystals using bilayer graphene: A new platform for engineering strongly correlated effects.

Z. E. Krix, **O. P. Sushkov**
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Superconductivity and correlated insulators have been observed in twisted bilayer graphene. Such effects arise because the relative twist between layers induces a long-wavelength lateral superlattice potential. These systems have been described as a kind of quantum simulator, however, their properties are not easily controlled. Most importantly, both the symmetry of the superlattice potential and the potential strength are fixed. In this talk I will describe an alternate system which is completely free of these restrictions: ordinary bilayer graphene with a patterned electrostatic gate. Here, the superlattice is designed and then etched, meaning that any lattice symmetry is possible. Moreover, the strength of the lattice potential can be tuned in situ. I will cover some of our theoretical work which indicates that this system has strong and tunable electron-electron correlations. I will also cover some of the recent experimental progress towards realising it.

Chester supersolid of spatially indirect excitons in double-layer semiconductor heterostructures

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The original supersolid, a counter-intuitive quantum state in which single-bosons that are localised on a rigid lattice flow without resistance, has to date not been unambiguously experimentally realised. Here we reveal a supersolid ground state of excitons [1] in a double-layer semiconductor heterostructure over a wide range of values of the layer separation that lie completely outside the focus of recent double- layer experiments. This supersolid conforms to the original Geoffrey Chester supersolid concept of one boson per supersolid site, as distinct from an alternative concept reported in cold-atom systems, of a periodic density modulation or a periodic clustering of a superfluid. We present the phase diagram augmented by the new supersolid phase. The new phase appears at layer separations much smaller than the separations that have been predicted for the exciton normal solid [2], and the supersolid persists up to a transition to the exciton normal solid, a solid-solid transition where the quantum phase coherence collapses. The ranges of layer separations and exciton densities in our phase diagram are well within reach of current experimental capabilities. Further avenues of investigation of this strikingly different quantum state of matter will be outlined.

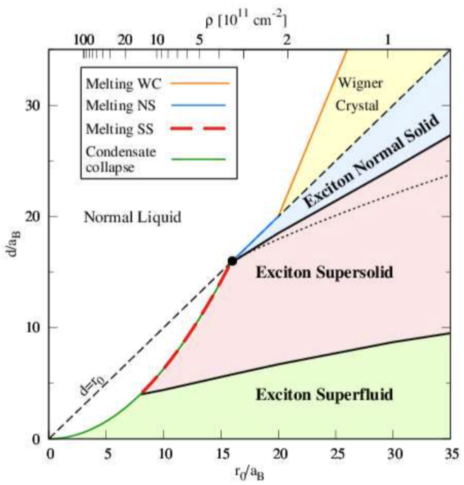

Figure 0.1: Phase diagram at zero temperature [1]. d is the separation of the electron and hole layers, r_0 characterises the equal electron and hole densities, both in units of the effective Bohr radius a_B. The dotted line shows the transition to the exciton normal solid predicted in Ref. [2]. The top axis shows, for reference, the density ρ for a typical double transition-metal dichalcogenide monolayer structure encapsulated in hexagonal Boron Nitride (see Ref. [3]).

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Exciton superfluidity in van der Waal heterostructures: Material specific screening from first principles

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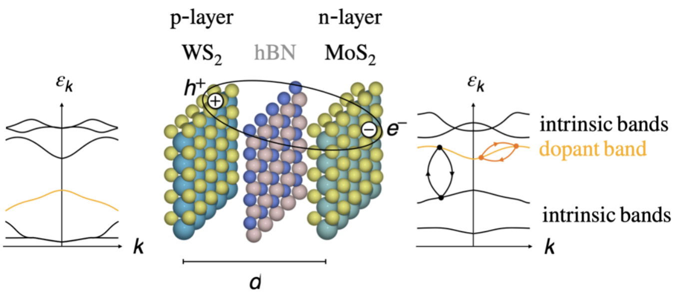
Van der Waal heterostructures, comprised of stacked 2D monolayer, has in recent years emerged as powerful platforms to design novel materials with tailored properties. An interesting phenomenon in these heterostructures are long lived excitons formed by spatially separated electron-hole pairs that can condense and exhibit superfluidity at low temperatures. Experimental evidence of exciton condensation has been found in both double bilayer graphene and MoSe2/WSe2 bilayers [1]. From a theoretical perspective, exciton condensation in these systems can be modelled by solving a mean-field gap equation defined for only the conduction and valence band of the electron and hole material respectively. In this talk we will discuss how to put such models in an ab initio framework by deriving the parameters of the model from first principles. In particular, we will focus on the effective electron-electron and electron-hole Coulomb interactions and show that these can be derived from the density functional theory band structures of the individual monolayers using already available open-source codes [2]. By applying this method to hundreds of different systems we will investigate material trends and suggest novel heterostructures with optimized properties [3].



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Josephson effect and superfluidity in electron-hole bilayer heterostructures

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We analyze the superfluid characteristics and crossover physics for Josephson junctions [1] in electron-hole bilayer TMD semiconductors [2]. We determine the critical current across junctions of different potential barrier heights [3,4]. We show that the crossover physics in the narrow barrier region controls the critical current throughout. We find that the ratio between the critical current and the carrier density exhibits an observable maximum at the density of the switchover from bosonic excitations to pair-breaking fermionic excitations [5]. This provides, for the first time in a semiconductor system, an experimental measure for the position of the boundary separating the BEC and BCS-BEC crossover regimes.

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BCS-BEC crossover in electron-hole double layer superfluids

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The fundamental interplay between the BCS-BEC crossover phenomenon and the high critical temperature electron-hole superfluidity in double layer systems will be discussed. Mean-field results with and without the inclusion of the self-consistent screening of the Coulomb interaction in the superfluid state and Quantum Monte Carlo simulations will be presented in a comparative way.

High-Tc electron-hole superfluidity can be achieved only when a large enough superfluid gap and a small or even negative chemical potential facilitated by low densities of carriers and strong electron-hole interlayer pairings are able to suppress the detrimental Coulomb screening, which otherwise would weaken too much the pairing of electrons and holes, forcing the system to remain in its Fermi liquid state. The opening of a large gap together with a complete smearing of the Fermi surface at low enough densities drain carriers from the Fermi sea, being them not any more available for the screening and opening the way to superfluid correlations.

We will conclude by reporting the universal phase diagram of the electron-hole superfluids in the temperature vs carrier density plane, locating the BCS-BEC crossover boundaries and summarizing its key role in the quest for achieving and controlling high-Tc electron-hole superfluidity.

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Monolayer WTe2 and pressurized MoS2 as ideal excitonic insulators

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We claim that $\mathrm{MoS_2}$ under pressure [1] and monolayer WTe 2 [2,3] are "excitonic insulators" (EIs). The longsought EI is a permanent Bose-Einstein condensate of excitons, electron-hole pairs bound by Coulomb interaction, which form in the absence of optical excitation. A surge of experimental claims has recently addressed layered materials, because of reduced Coulomb screening. However, the transition to the putative bulk EI is ubiquitously accompanied by the softening of a phonon inducing a structural change; therefore it remains unclear whether the observed phase is genuinely excitonic or instead stabilized by electron-phonon interaction.

Our calculations from first principles [1] show that $\mathrm{MoS_2}$ for a range of applied pressure is unstable against the spontaneous generation of excitons but stable against lattice distortion. We predict that the EI is an antiferroelectricic, electronic density wave. At the onset of the EI phase, those optical phonons that share the exciton momentum provide a unique Raman fingerprint for the EI formation. We identify such fingerprint in a Raman feature that was previously observed experimentally, thus providing direct spectroscopic confirmation of an EI phase in bulk $\mathrm{MoS_2}$ above $30\mathrm{GPa}$.

Furthermore, we present theoretical [2,3] and experimental [3] evidence that the two-dimensional bulk of monolayer $\mathrm{WTe_2}$ contains excitons that spontaneously form in thermal equilibrium. On cooling from room temperature to $100\ \mathrm{K}$, the conductivity develops a V-shaped dependence on electrostatic doping, while the chemical potential develops a step at the neutral point. These features are much sharper than is possible in an independent-electron picture, but they can be accounted for if electrons and holes interact strongly and are paired in equilibrium. Our calculations from first principles show that the exciton binding energy is larger than $100\mathrm{meV}$ and the radius as small as $4\ \mathrm{nm}$, explaining their formation at high temperature and doping levels. Below $100\ \mathrm{K}$, more strongly insulating behaviour is seen, suggesting that a charge-ordered state forms. The observed absence of charge density waves in this state is surprising within an excitonic insulator picture, but we show that it can be explained by the huge exchange interaction affecting excitons. Therefore, in addition to being a topological insulator, monolayer $\mathrm{WTe_2}$ exhibits strong correlations over a wide temperature range.

This work is done in collaboration with Elisa Molinari, Daniele Varsano, Samaneh Ataei, Maurizia Palummo, David Cobden, and it is partially funded by MUR PRIN2017 No. 2017BZPKSZ "EXC-INS".

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Excitations in a symmetric electron-hole bilayer: quasiparticles excitation energies, collectiveexcitations

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I shall start with a very brief and incomplete review of theoretical proposals and lab fabrications of solid state devices supporting indirect excitons, over the last 48 years. I shall then provide the model that we study a paramagnetic, symmetric electron-hole bilayer with twofold valley degeneracy (SEHB2V; $m_e = m_h = m_b, g_{\rm v} = 2$), summarizing the basic ingredients of our QMC simulations and providing just a few results that are necessary for this presentation. A full, detailed account of our simulations for the ground state properties $[1, 2]$ will be presented in a companion talk by Stefania De Palo. Here, I am going to examine two kinds of excitations of the SEHB2V, namely (i) quasiparticles excitations and (ii) collective excitations. The investigation of quasiparticle excitation energies for the paramagnetic, symmetric electron-hole bilaye (SEHB) was performed a few years ago [3]. Here we present preliminary results for a similar investigation when valley degeneracy is present. It turns out that qualitative aspect of the energy dispersions in the SEHB2V and SEHB are similar. In the presence of a Bose Einstein Condensate it is customary to identify [3] a BEC regime, a BCS regime and a Crossover regime. We find that in the SEHB2V the excitonic phase is always in the Crossover regime. The treatment of collective excitations is evidently much more difficult to address with QMC than quasiparticle excitations. We therefore resort to an approximate scheme We have recently extended to electron-hole bilayers [4] the quantum continuum mechanics (QCM) formalism [5], which expresses excitation energies of collective modes at in terms of ground-state pair correlation functions and kinetic energy. In the second half of the talk I shall illustrate the application of such scheme to the SEHB2V, focussing on the finite gap for in the mode frequency of the charged channell.

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Excitonic insulator in atomic double layers: an experimental realization

<u>Jie Shan</u>
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Excitonic insulators have been proposed as a solid-state platform for quantum many-boson physics. Although the concept of an excitonic insulator has been understood for sixty years, it remains challenging to establish distinct experimental signatures of its realization. In this talk, we will discuss the recent development of transition metal dichacogenide double layer structures and electrical injection of interlayer excitons up to $10^12/cm^2$. We establish electrical control of the chemical potential of interlayer excitons and probe their thermodynamic properties by capacitance measurements. We will present experimental evidence for an excitonic insulating phase and discuss the possibility of probing exciton superfluidity.