# 2nd Workshop of the Melbourne Condensed Matter Community (MC²)

**Friday November 16, 2018**  
8:50 – 16:00  
Monash University, New Horizons G29/G30

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:50</td>
<td>Welcome</td>
<td>Welcome (Julie Karel)</td>
</tr>
<tr>
<td><strong>Chair: Agustin Schiffrin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:00</td>
<td>Lan Wang</td>
<td>“2D ferromagnetism and spintronic devices based on van der Waals heterostructures”</td>
</tr>
<tr>
<td>9:30</td>
<td>Antonija Grubisic-Cabo</td>
<td>“Influence of the underlying substrate on electronic structure and free carrier dynamics in 2D transition metal dichalcogenides”</td>
</tr>
<tr>
<td>10:00</td>
<td>Morning tea and discussions</td>
<td></td>
</tr>
<tr>
<td><strong>Chair: Semonti Bhattacharyya</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td>Jamie Booth</td>
<td>“Is there a Standard Model for Condensed Matter Physics?”</td>
</tr>
<tr>
<td>11:30</td>
<td>Harry Quiney</td>
<td>“Reduced density matrix approach to many-fermion systems”</td>
</tr>
<tr>
<td>12:00</td>
<td>Lunch and student poster session</td>
<td></td>
</tr>
<tr>
<td><strong>Chair: Julie Karel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:00</td>
<td>Anton Tadich</td>
<td>“Angle Resolved Photoelectron Spectroscopy (ARPES) at the Australian Synchrotron”</td>
</tr>
<tr>
<td>14:30</td>
<td>Jean-Philippe Tetienne</td>
<td>“Diamond-based quantum sensing: applications to condensed matter systems”</td>
</tr>
<tr>
<td>15:00</td>
<td>Afternoon tea and discussions</td>
<td></td>
</tr>
<tr>
<td><strong>Chair: Amadeo Lopez Vazquez de Parga</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:30</td>
<td>Cornelius Krull</td>
<td>“Towards Artificial Intelligence driven Scanning Probe Microscopy”</td>
</tr>
<tr>
<td>16:00</td>
<td>Sascha Hoinka</td>
<td>“Elementary excitations of a fermionic superfluid with strong inter-particle interactions”</td>
</tr>
<tr>
<td>16:30</td>
<td>Concluding remarks (Julie Karel/Agustin Schiffrin)</td>
<td></td>
</tr>
</tbody>
</table>

**NEXT WORKSHOP:** Fri. June 7, 2019 @ RMIT University
“2D ferromagnetism and spintronic devices based on van der Waals heterostructures”

Lan Wang
RMIT University

Two dimensional (2D) van der Waals (vdW) materials, consisting of atomically thin layers, have fascinating physical properties and intriguing thickness-dependent characteristics. To date, research on these materials has predominantly focused on various devices based on their optical and electronic properties, whilst reports on magnetic and spintronic devices based on 2D vdW materials are scarce, because vdW materials with desirable magnetic properties have yet to be found. By performing anomalous Hall-effect transport measurements, we reveal that the magnetic properties of single crystalline vdW Fe$_3$GeTe$_2$ vary dramatically with thickness. Importantly, a single hard magnetic phase with a near square-shaped magnetic loop, large coercivity (up to 550 mT at 2 K) and strong perpendicular magnetic anisotropy were all observed in Fe$_3$GeTe$_2$ nanoflakes. These merits make Fe$_3$GeTe$_2$ the first vdW ferromagnetic material suitable for fabricating vdW magnetic heterostructures. Based on this material, various spintronic devices has been designed and fabricated.


“Influence of the underlying substrate on electronic structure and free carrier dynamics in 2D transition metal dichalcogenides”

Antonija Grubisic-Cabo
Monash University

Two-dimensional transition metal dichalcogenides (2D TMDCs) have generated significant interest in the scientific community thanks to their remarkable optical and electronic properties. Due to reduced dimensionality and atomic thickness, electronic properties in 2D TMDCs, including the band gap, are drastically different from their parent compounds. The electronic properties of 2D materials do not only depend on the material, but also on its environment and are, for example, extremely sensitive to the properties of the supporting substrate. Consequently, the properties of the material can be changed depending on the substrate in use, the environment surrounding the TMDC, and even the carrier concentration within the 2D material. Besides control of the electronic band gap, control of the spin- and valley-degrees of freedom has been suggested as a new, potential tuning knob for carrier dynamics, and semiconducting 2D TMDCs are particularly promising candidates for new spin- and valley-tronic devices.

In this talk I will present work from my PhD at Aarhus University on the ultrafast dynamics of free carriers and on valley-degrees of freedom in 2D TMDCs (MoS$_2$, WS$_2$) probed by the time- and angle resolved photoemission spectroscopy (TR-ARPES) technique and show more recent work from Monash University on the effect of substrate properties on electronic structure and optoelectronic properties of WS$_2$. 
There currently exist a number of seemingly intractable problems in Condensed Matter physics (by intractable it is meant that some decades have passed since they were first identified without a solution being found). Mechanisms of metal-insulator transitions in metal oxides [1], [2] and high temperature superconductivity in the cuprates and pnictides are two examples [3], [4]. In addition, the cooperative interplay of magnetism and lattice distortions has also been emphasized in layered transition-metal dichalcogenides [5]–[7]. Since the early years of the development of quantum mechanics, Condensed Matter physics has developed theories built around specific Hamiltonians which are limiting cases of the general behavior of condensed, non-relativistic quantum systems, such as the Heisenberg Ferro-/Antiferromagnet, the Hubbard Model [8] and its simplification the $t$-$J$ model [9], the perturbative Peierls Mechanism of metal-insulator transitions [10], and the BCS theory of superconductivity [11].

The purpose behind this work is to explore whether such seemingly disparate phenomena can arise from a single, simple, underlying theory. In other words, can a theory of interacting particles be written down which unifies these models into some deeper structure in the same way that the Standard Model of Particle Physics unifies the Strong-, Weak- and Electromagnetic Forces. It is shown that by reinterpreting lattices and their fluctuations in terms of an SU(2) Yang-Mills theory [12], [13], that a wealth of interesting phenomena arise, including a mechanism of unconventional superconductivity [14].

Reduced density matrix approach to many-fermion systems

Harry Quiney
University of Melbourne

Conventional approaches to understanding the properties of many-electron systems, particularly in atomic and molecular physics and quantum chemistry, are based either on the solution of the Schrödinger equation for the N-particle wavefunction or the Kohn-Sham equations of density functional theory for the single-particle electron density. The appeal of wavefunction-based methods is that the approach to exact representations is well-understood, albeit at a cost that grows exponentially with the complexity of the problem. In contrast, density functional theory is computationally expedient but relies on functionals that are necessarily approximate representations of the underlying theory. The use of reduced density matrices represents a less well-developed “third way”. The first appearance of the reduced density matrix occurred in 1929 in a paper by Dirac and by the 1940s it was recognised that any electronic property of interest in atomic, molecular and solid state physics could be calculated exactly from the two-electron density matrix. Attempts to work directly with the two-electron density, rather than the N-electron wavefunction, were frustrated by the N-representability problem; the need to impose constraints on the density that established its origins in a valid N-electron wavefunction [1]. Despite intense efforts, this difficulty took at least fifty years to resolve. In 2012, Mazziotti finally published a systematic prescription for the construction of two-electron density matrices derivable from N-electron wavefunctions and a variational scheme to determine the properties of any electronic system directly from the density matrix formalism at polynomial cost [2,3]. In this presentation we will review the development and current limitations of the use of reduced density matrices in electronic structure theory, potential applications to other systems of fermions and recent suggestions [4] that this approach has the potential to exploit the limited capabilities of the first generation of quantum computers.


Angle Resolved Photoelectron Spectroscopy (ARPES) at the Australian Synchrotron

Anton Tadich
Australian Synchrotron

Angle Resolved Photoelectron Spectroscopy (ARPES) is the “complete” photoemission experiment. By simultaneously measuring the outgoing photoelectron’s kinetic energy and emission angle relative to the crystallographic axes of a sample, one is able to obtain a direct image of the electronic bandstructure and associated topology (such as the Fermi Surface). To this day, ARPES remains the most powerful technique for determining the electronic structure of crystalline and periodic condensed matter systems. The technique has been instrumental in the discovery and understanding of new electronic phases of matter. For example, important aspects of the electronic structure of high-Tc superconductors, such as the pseudogap were discovered using ARPES, as was the experimental discovery of three dimensional topological insulators $\text{Bi}_2\text{Se}_3$ and $\text{Bi}_2\text{Te}_3$. Over the years, a dramatic improvement in the energy and momentum resolution possible with ARPES has occurred as a result of advances in photoelectron analysers and 2D detectors, allowing a range of new physics to be probed.

Despite the popularity of ARPES at overseas light sources, it has until now remained as a niche technique in Australia due to a small user community. However, the continually growing local interest in studying novel materials with exotic electronic properties has led to the demand for our own synchrotron – based ARPES instrument. Australia’s first ARPES detector, a “toroidal” geometry analyser, is now installed at the Soft X-ray beamline at the Australian Synchrotron, with initial commissioning completed and first experiments conducted. An overview of the basic principles of ARPES will be given, followed by a detailed overview of the instrument. Finally, a summary of the latest hardware developments on the instrument will be presented.
The nitrogen-vacancy (NV) defect in diamond is a point defect that can be used as a nanoscale quantum sensor to provide sensitive measurements of the local magnetic field, electric field or lattice strain, for example. In this talk, I will present our recent efforts to apply NV-diamond sensing to the study of condensed matter systems, including the imaging of current flow in graphene-based field effect transistors and of surface band bending in devices based on the 2D hole gas formed at the diamond surface.

Scanning Probe Microscopy (SPM) is a powerful surface characterisation technique that has revolutionised many scientific fields, from nanoscience to biology. It allows for the recording of atomically resolved image data, providing insight into material properties such as the electronic structure and chemical bonds. Moreover, SPM enables the manipulation of the geometry of nanoscopic systems with atomic precision. However, obtaining data with optimal atomic-scale resolution and achieving stable operation require an expert user who monitors and controls the experimental conditions, in particular the state of sample and probe. Consequently, advanced SPM is mainly used in specialist research laboratories. Here, we present an Artificial Intelligence driven SPM (AId-SPM), allowing for fully autonomous SPM optimization and data acquisition. We demonstrate that AId-SPM responds adequately to the varying experimental conditions and allows for experiments without human supervision. AId-SPM relies on machine learning, providing algorithmic solutions for the various issues arising during SPM operation. Importantly, it addresses the complex in-situ management of the probe, by assessing its quality with convolutional neural networks and subsequently conditioning it via deep reinforcement learning.

Our machine learning approach paves the way for the use of SPM in a broad range of scientific and commercial fields. It reduces the need for expert supervision and has the potential to lead to advanced SPM techniques hardly achievable via human operation, such as large dataset acquisition for statistical analysis or SPM-based nanolithography.

We explore the temperature dependence of the elementary excitations across the superfluid phase transition in a homogeneous unitarity Fermi gas using low-momentum Bragg spectroscopy. At long wavelength, Bragg scattering probes collective excitations of the gas which are closely linked to the superfluid order parameter. In the experiments, we shine two tightly focussed laser beams into the central, nearly homogeneous, volume of an optically trapped cloud of lithium-6 atoms with equal spin population and measure the density-density response. The dominant feature in the measured Bragg spectra is a peak corresponding to the phonon mode, which dramatically changes in both amplitude and width across the superfluid to normal fluid transition. We can use this to study dynamic properties such as damping and the evolution of the speed of sound. This allows us to not only investigate phonon scattering processes in more detail but also to link the density response to the thermodynamics of the system via the pressure equation of state.