Optical Science Centre – Quantum Optics Spectroscopy 2021 Physics Honours Projects

1. 2D Fermi Gases near a p-wave Feshbach resonance

Supervisors: Professor Chris Vale, Dr Paul Dyke, Dr Ivan Herrera
Contact: cvale@swin.edu.au

Project description: Ultracold atomic gases can display several remarkable quantum behaviours at nanoKelvin temperatures such as superfluidity or flow with zero resistance. In Fermi gases, superfluidity relies on atoms forming pairs and to date only the simplest form pairing has been successfully used. In this project you will take steps towards forming p-wave pairs in a 2D Fermi gas. This will involve measuring the lifetime of atoms near a p-wave Feshbach resonance which is predicted to be much longer in 2D. Depending on the magnitude of the lifetime enhancement, we will attempt to evaporatively cool a gas to superfluidity near the p-wave Feshbach resonance. We will also investigate the effect of p-wave impurities in cold gases and the p-wave polaron and the behaviour of quantum gases following a rapid quench of the interactions.

2. An ultracold source of Dy atoms

Supervisor: Prof. Chris Vale, Dr Sascha Hoinka and Dr Ivan Herrera
Contact: cvale@swin.edu.au

Project description: The Australian Quantum gas microscope is a new facility being constructed at Swinburne for the study of quantum superfluids and topological matter using ultracold gases of dysprosium atoms. The apparatus is currently being designed and built in a new laboratory. We have various project available that will contribute to the construction of this system including the design and testing of a Dy fountain and magneto-optical traps, experimental control and imaging systems.

3. Dynamics and interactions of exciton-polaritons in semiconductor microcavities

Supervisors: Associate Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: A polariton is a quasi-particle that is part photon and part exciton (where an exciton is a bound electron-hole pair). These part light – part matter quasi particles arise where there is strong light-matter coupling, such as is the case where 2D materials or quantum wells are incorporated within a light cavity formed by two mirrors. These polariton systems offer great flexibility to control the properties of and interaction between polaritons and form condensed phases of matter that allow for loss-less energy flow. In this project, you will use femtosecond (10^{-15} s) laser pulses and state of the art multidimensional coherent spectroscopy experiments to measure the dynamics and interactions between polaritons and excitons in GaAs quantum wells. This work is part of the Centre of Excellence for Future Low-Energy Electronic Technologies, where we hope to be able to find a way to utilise the unique properties of polaritons for next generation electronics solutions.

4. Coherent Dynamics in High-Temperature Superconductors

Supervisors: Associate Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: Understanding the mechanisms of high-temperature superconductivity has been one of the great challenges in condensed matter physics over the past 30 years since superconductivity was first observed in cuprate materials. In the past 12 months we have been able to successfully realise the first measurements of coherent dynamics in these materials, which we expect will help to provide great insight into the mechanisms responsible for superconductivity in these materials[1]. This project will expand upon that work, measuring the coherent dynamics using femtosecond (10-15 s) laser pulses and state of the art multidimensional coherent spectroscopy experiments.

[1] Novelli, Tollerud, Davis Science Advances 6, eaaw9932 (2020), https://doi.org/10.1126/sciadv.aaw9932

5. Floquet Physics in Atomically Thin 2D Semiconductors Supervisors:

Supervisors: Associate Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: The bandstructure of a material plays a major role in describing its properties, and usually doesn’t change. Floquet physics provides a pathway to reversibly alter and control the bandstructure of materials through the application of a time-periodic perturbation. In this project you will use the oscillating electromagnetic field of a laser pulse as the periodic perturbation and use it to alter the bands and properties of two-dimensional semiconductors that are one atom thick. With the unique properties of these 2D materials and the control of the bandstructure allowed through Floquet physics it is predicted to be possible to generate exciting new types of quantum materials and switch them on and off. You will probe these states with state-of-the-art coherent multidimensional spectroscopy capabilities developed at Swinburne to reveal coherent dynamics and the physics underlying the switching on and off of the applied field. This project is part of the ARC Centre of Excellence for Future Low-Energy Electronics Technologies (FLEET: www.fleet.org.au), and aims to reveal new physics that can underlie a new paradigm for electronics technologies.

6. Exploring the role of Quantum Coherence and Electronic-Vibrational Coupling in Photosynthesis

Supervisors: Associate Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: Photosynthesis takes place in the warm, wet environment of biological systems, which at first glance seems an unlikely place to find and explore the clear effects of quantum mechanics. Recent work has identified the presence of long-lived coherences among different molecules within some light-harvesting complexes involved in photosynthesis. Using the techniques developed here at Swinburne, we are able to study directly these quantum mechanical processes in detail. This project will explore the role of quantum coherence and electronic-vibrational coupling in photosynthesis by studying the dynamics of both coherent and classical energy transfer, within the isolated molecules and between the molecules within light-harvesting complexes. The ultimate aim is to develop an in depth understanding of the mechanisms responsible for the efficient energy transfer in photosynthesis.

7. Quantum Turbulence (theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

Quantum turbulence occurs in superfluids and is associated with chaotic dynamics of quantised vortices. These non-equilibrium quantum systems feature remarkable behaviours such as absolute negative temperature states and large scale Onsager vortex flows. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.

[1] S. Johnstone et al. Evolution of large-scale flow from turbulence in a two-dimensional superfluid, Science 364, 1267 (2019).

8. Superwalkers (experiments/theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

Millimeter sized droplets can be made to bounce on the surface of a periodically driven fluid. For suitably Floquet engineered parameters these droplets begin to "walk" at speeds exceeding tens of millimeters per second. Furthermore, these curious wave-droplet entities have been shown to mimic the behaviour of various quantum systems. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.

[1] R. Valani et al. Superwalking Droplets, Phys. Rev. Lett. 123, 024503 (2019).

9. Topological Quantum Computation (theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

The future of computing inevitably involves quantum computers. Topological quantum computation is a novel decoherence resilient way of performing quantum information processing and may be achieved using novel particles called non-Abelian anyons, which are neither bosons or fermions. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.

[1] B. Field et al. Introduction to topological quantum computation with non-Abelian anyons, Quantum Science and Technology 3, 045004 (2018).

10. Four Wave mixing in extreme ultraviolet region for study of molecular dynamics

Supervisor: Prof Lap Van Dao
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Project Description: The high-order harmonic generation process provides methods to produce short pulses of coherent radiation in the extreme ultraviolet (EUV) and soft X-ray region. High-order harmonic generation involving the interaction of atoms or molecules with strong laser fields is an example of nonlinear optics. Using two or three femtosecond laser pulses with different carrier frequencies the EUV four-wave mixing fields can be created. The four-wave mixing emission can be manipulated by varying the delay between the optical pulses and information about the dynamics of molecular systems can be obtained. The aims of this project are the use of multiple laser fields with controllable intensity and carrier frequency for investigation of quantum effects of molecular systems such as N_2 or O_2 in the extreme ultraviolet region.

11. Gravitational Bouncer with Ultracold Atoms

Supervisor: Prof Peter Hannaford and Prof Andrei Sidorov
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Project Description: This project involves the creation of a cloud of ultracold potassium-39 atoms, and ultimately a Bose-Einstein condensate, bouncing on an atom mirror. This experiment is a forerunner to producing a 'time crystal' of ultracold atoms which is a new form of quantum matter in which a periodically driven many-body system repeats itself in time, rather than in space, with a period longer than the driving period, allowing the periodic structure to resist external perturbations and to persist for long periods of time. Such time crystals have potential application in condensed matter physics in the time domain, quantum technology and atomic clocks.

Further reading: Physics World, https://physicsworld.com/a/in-search-of-time-crystals/; https://physicsworld.com/a/time-crystals-enter-the-real-world-of-condensed-matter/