Swinburne Physics Honours 2020 Projects

This is the list of projects for 2020. Please also check the web pages of the Research Centres and feel free to contact researchers for possible honours projects.

List

Centre for Quantum and Optical Science (CQOS)

1. 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).

2. 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).

3. 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).

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

Supervisor: Lap Van Dao Honours Project (dvlap@swin.edu.au)

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.

5. Table-top Cosmology with Ultracold Atoms

Supervisors: Professor Andrei Sidorov and Professor Peter Drummond
Contact: asidorov@swin.edu.au

Project description: The area of ultracold atoms is a burgeoning field of research with an unprecedented ability to mimic complex physical phenomena in a table-top experiment in clean and carefully controlled environment. This project focuses on the application of a Bose-Einstein condensate as a quantum simulator of the early Universe inflation. Under appropriate conditions the scalar field describing the cosmological "Big Bang" and the relative phase of two Bose condensates are described by the same equations, with terms analogous to the speed of light and the Hubble constant. This project will target different scenarios of simulating the Big Bang with Bose condensates.

Further reading:

http://www.swinburne.edu.au/engineering/caous/bec_on_a_chip.htm

6. Josephson Junction with Ultracold Atoms

Supervisor: Professor Andrei Sidorov
Contact: asidorov@swin.edu.au

Project description: The Josephson effect is a remarkable manifestation of macroscopic quantum coherence. A solid-state Josephson junction is made of two superconductors separated by a thin insulating layer where the current is driven by the phase of two wavefunctions. The Honours project will focus on the study of an ultracold Josephson junction where two Bose-Einstein condensates (BEC) are coupled by the microwave field and exhibit ultimate coherent properties. Numerous fascinating quantum effects were predicted and are still to be observed. The project will target practical implementations of the BEC Josephson junction for quantum sensors and metrology and involve theoretical modelling and experimental investigations.

Further reading: http://www.swinburne.edu.au/engineering/caous/bec_on_a_chip.htm

7. 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. (When an electron is excited from the valence band into the conduction band, it leave behind a hole, with effective positive charge. The electron and hole experience a Coulomb attraction much like the electron and proton in a hydrogen atom, forming an exciton.) In this project, you will use femtosecond (10^{-15} s) laser pulses and state of the art coherent multidimensional 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.

8. 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. This project will continue and extend that work, measuring the coherent dynamics using femtosecond (10^{-15} s) laser pulses and state of the art coherent multidimensional spectroscopy experiments.

9. Floquet Physics in Atomically Thin 2D Semiconductors

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

Project description: This project is part of the ARC Centre of Excellence for Future Low-Energy Electronics Technologies (FLEET: www.fleet.org.au). Here you will utilise femtosecond laser pulses to transiently alter the band structure of 2D semiconductors by driving so-called "Floquet-Bloch" states.

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. Understanding this transient switching will help to realise and understand Floquet topological insulators.

Further reading: www.swin.edu.au/caous/UltrafastSpec.htm

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

Supervisors: Associate Professor Jeffrey Davis

Contact: jdavis@swin.edu.au

Project description: Recent work has identified the presence of long-lived coherences amongst different molecules within some light-harvesting complexes involved in photosynthesis. Using the techniques developed here at Swinburne, we are able to study directly the sequantum 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.

Further reading:

www.swin.edu.au/caous/UltrafastSpec.htm

11. 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.

12. Bragg spectroscopy of ultracold gas and linear response

Supervisor: Dr Carlos Kuhn and Prof. Chris Vale (cvale@swin.edu.au)

Project description: Elementary excitations are interesting and fundamental to the understanding of transport properties of a fluid (gas). This project has the goal to understand the effects of the probe in the measurement. We will theoretically lift the veil of the linear response by understanding its limitations when applied to a fermi gas at degeneracy. The final goal is to get an analytical expression and numerical simulations that would describe quantitively the experimental results obtained by the Fermi Group at Swinburne

13. An ultracold source of Dy atoms

Supervisor: Prof. Chris Vale, Dr Sascha Hoinka and Dr Ivan Herrera (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 the 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.

14. Few-body Physics and Virial Expansions

Supervisor: Professor Xia-ji Liu (xliu@swin.edu.au)

Project description: Few-body systems have become increasingly crucial to the physics of strongly correlated ultracold atomic gases. Because of large interaction parameters, conventional perturbation theory approaches such as mean-field theory, simply break down.
A small ensemble of a few fermions and/or bosons, which is either exactly solvable or numerically tractable, is more amenable to non-perturbative quantal calculations. The few-body solutions can be efficiently used for investigating high temperature properties of strongly correlated quantum gases, through the well documented virial expansion method.

This Honours project will investigate few-body exact solutions and high-temperature properties of ultracold atomic gases with s-wave and p-wave interactions. In particular, the project will focus on the few-body solutions of a one-dimensional Bose/Fermi gas and obtain several low-order virial expansion coefficients.

15. Theory of One-Dimensional Fermi/Bose Polarons

Supervisor: Professor Hui Hu
Contact: hhu@swin.edu.au

Project description: The theory of strongly interacting fermions/bosons is of great interest. Interacting fermions/bosons are involved in some of the most important unanswered questions in condensed matter physics, nuclear physics, astrophysics, and cosmology. Though weakly interacting fermions/bosons are well understood, new approaches are required to treat strong interactions. In these cases, one encounters a “strongly correlated” picture which occurs in many fundamental systems ranging from strongly interacting electrons to quarks.

This project will consider a simplified case of “polarons”, which involves one impurity immersed in a background of N fermions or bosons. In this N+1 problem, the strongly interaction between impurity and background atoms might be handled. To further simplify the problem, we will focus on the one-dimensional situation by using the Bethe Ansatz technique. The results of this project can be tested in future coldatom experiments.

16. Tests of Macro and Local Realism using Entangled Twin Beams and Bose-Einstein Condensates

Supervisor: Professor Margaret Reid (mreid@swin.edu.au)

Project description: Schrodinger puzzled over the interpretation of the quantum mechanical state where a system is in a superposition of two macroscopically distinguishable states. He considered the odd case where apparently, according to the Copenhagen interpretation of quantum mechanics, a cat could be simultaneously dead and alive. The odd predictions of quantum mechanics can be rigorously shown different to those of a whole class of classical theories based on no 'spooky action at a distance' and the idea that a system is predetermined to be in a state prior to measurement.

This is a theoretical project that will study how to realise such regimes of quantum predictions using optical or atomic entangled systems. The project will utilize and develop extensions of Leggett-Garg and Bell inequalities that apply to practical atomic systems.

17. Projects on Theoretical Quantum Physics

Supervisor: Professor Peter Drummond (pdrummond@swin.edu.au)

18. Gravitational Bouncer with Ultracold Atoms

Supervisors: Peter Hannaford and Andrei Sidorov (asidorov@swin.edu.au)
This is a new experiment currently under construction. It will involve the study of ultracold atoms (a Bose-Einstein condensate of potassium-39 atoms) bouncing on an oscillating atom mirror. The bouncing potassium-39 atoms will be confined transversely by an optical waveguide which should allow a large number of bounces. The aim is to achieve of the order of 50 bounces, which is much higher than in previous experiments. This experiment will be 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 fluctuations and to persist for long period of time. Such time crystals have potential application in non-equilibrium condensed matter physics, quantum technology and atomic clocks.