

# Centre for Quantum and Optical Science – Theoretical Physics 2021 Honours Projects

## 1. Quantum Paradoxes

**Supervisor:** Professor Margaret D. Reid ([mdreid@swin.edu.au](mailto:mdreid@swin.edu.au) )

**Project description:**

Quantum mechanics gives rise to many paradoxes. Some, like Bell's theorem and Leggett-Garg tests of macro-realism result in no-go theorems that underpin the field of quantum information. The aim of this project is to investigate the macroscopic nature of quantum paradoxes, to examine the implication of the nature of measurement, and to probe possible applications for quantum information.

## 2. Quantum Networks

**Supervisor:** Professor Peter D. Drummond ([pdrummond@swin.edu.au](mailto:pdrummond@swin.edu.au) )

**Project description:**

Quantum networks are coupled linear or nonlinear quantum systems which are being increasingly studied both for their fundamental interest and for applications to quantum technologies. This project will study nonlinear simplex networks, to analyse ground states and dynamics of interconnected simplexes. These can be implemented in several ways, using optical lattices of ultracold atoms, coupled optomechanical devices or waveguides and superconducting Josephson devices.

## 3. Theory of One-Dimensional Fermi/Bose Polarons: A/Prof. Hu and Prof. Liu

**Supervisors:** A/Prof Hui Hu and Prof Xia-ji Liu ([hhu@swin.edu.au](mailto: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 cold atom experiments.

**Reference:** Hui Hu, Peter Drummond, and Xia-Ji Liu, *Nature Physics* 3, 469 (2007).

#### 4. Few-body physics and virial expansions

**Supervisors:** Prof Xia-ji Liu and A/Prof Hui Hu ([xjia@swin.edu.au](mailto:xjia@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.

**Reference:** Xia-Ji Liu, *Physics Reports*, Vol 524, Issue 2, Pages 37-83 (2013).

#### 5. Ultradilute quantum droplets

**Supervisors:** A/Prof Hui Hu and Prof Xia-ji Liu ([hhu@swin.edu.au](mailto:hhu@swin.edu.au))

**Project description:** Over the past few years, a newly discovered phase of ultracold, dilute

quantum droplets has attracted increasingly attention in different fields of physics. In sharp contrast to other gas-like phases in containers, quantum droplets are self-bound, liquid-like clusters of ten to hundred thousands of atoms in free space, formed by the delicate balance between the attractive mean-field force and repulsive force from quantum fluctuations. The purpose of this project is to develop better microscopic theories of quantum droplets and to solve some challenging theoretical difficulties in this field.

This Honours project will focus on the theory of quantum droplets in low-dimensional and mass-imbalanced binary Bose mixtures. Furthermore, the project will explore collective excitations of an ultradilute quantum droplet.

**Reference:** Xia-Ji Liu, Hui Hu, A Minguzzi, and M.P. Tosi, *Physical Review A* 69, 043605 (2004).

## 6. Ultracold Atoms with Synthetic Spin-Orbit Coupling

**Supervisors:** Prof Xia-ji Liu and A/Prof Hui Hu ([xjia@swin.edu.au](mailto:xjia@swin.edu.au))

**Project description:** Recent realization of synthetic gauge fields in ultracold atoms, i.e., the creation of a spin-orbit coupling between the spin and the orbital degrees of freedom, has led to a new frontier that is endowed with a strong interdisciplinary character and a close connection to other research fields, including condensed matter physics, quantum computation and astrophysics.

This Honours project will investigate the characterization of novel topological fermionic superfluids and possible exotic Bose-Einstein condensates (BECs) with non-trivial spin-textures.

**Reference:** Hui Hu, B. Ramachandhran, Han Pu, and Xia-Ji Liu, *Physical Review Letters* 108, 010402 (2012).