Centre for Quantum Technology Theory – Theoretical Physics 2023 Honours Projects

1. Quantum Paradoxes

Supervisor: Professor Margaret D. Reid (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)

Project description:

The project will focus on quantum simulations of current network experiments. There are two choices: a large-scale boson sampling experiment commencing shortly at Cornell, which generates uncomputable random bits, and a commercial machine called the coherent Ising machine. This solves optimization problems called NP-complete max-cut graph problems, which have many real-world applications. Both experiments examine the question of quantum supremacy, that is, whether a quantum device can carry out a computation that a classical one is unable to. Therefore, to investigate this requires scalable methods that approach this in a more subtle way. These simulate quantum correlations and success probabilities, rather than classical brute force direct methods that are known to take billions of years.

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)

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 (xiajiliu@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)

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 (xiajiliu@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).