Open quantum dynamics of ultracold fermions

Ultracold atom research has seen unprecedented advances in the control and measurement of the quantum state of many thousands of interacting particles. However, nearly all measurements involve the destruction of the sample. Consequently, to probe directly the dynamics of the gas, one must repeatedly prepare and evolve independent samples to build up a time sequence of images, giving rise to shot-to-shot variations in the measurement.

The aim of this area of research is to develop the theory of nondestructive measurements of degenerate fermi gases. Currently, optical cavities provide the most promising means of allowing efficient measurements without destroying the ultracold gas. The projects in this area will investigate the quantum dynamics of ultracold fermi gases under continuous observation. A crucial question is how the quantum mechanical back-action from the measurement affects the dynamics of the atoms.

Dynamics of ultracold fermions in the optical cavity system

The emphasis here is on continuous, dispersive measurements, with a significant opportunity here for developing stochastic unravelling techniques for fermions (such techniques originated in the field of quantum optics and were thus formulated for bosons). A direction to be explored is feedback schemes for fermions, in analogy with current work on the atom laser. Other applications include exploring BCS-BEC crossover physics using homodyne measurement, and using cavities in combination with “twin beams” to detect EPR- and Bell-type correlations.

Interferometers with fermions in a double-well potential

The double-well system has been a popular choice for exploring the essential quantum features of degenerate gases of bosons, and can be expected to play a similar role for fermions. The fermionic case would allow a more direct realisation of (AC) Josephson tunnelling than does a BEC in a double well, but with the experimental purity and accessibility provided by the ultracold realisation. The first two tasks to be completed are (1) a more comprehensive study of homodyne measurements of a BEC, going beyond the simple models that have so far been used and (2) a first (two-mode) implementation of fermions in a cavity for continuous measurement. In the later stages of the project, the double-well configuration will be used to investigate the interferometric applications (for precision measurement) of nondestructive measurements schemes.

Development of advanced computational methods

There aim here to utilise the Gaussian phase-space representations to develop powerful methods for simulating multimode fermion dynamics. The Gaussian approach is naturally suited to studying open systems and will allow a "quantum-noise" approach for fermionic systems. For the real-time dynamics of fermions, the formalism has been developed and is ready to be applied to specific applications. Although the methods can be applied 'as is' for
short-time simulations, longer simulation times require gauge optimisations, or else approximate 'classical field' approaches, which are also possible within the Gaussian phase-space approach.

Technically, these projects will make use of a combination of analytic and numerical approaches. Much of the numerical work could be done with with matlab or XMDS (in-house simulation package), but some aspects will require lower level extensions in C/fortran. Some background knowledge in quantum optics or ultracold atoms would be useful.

**Other project areas:**

**Quantum Squeezing in Photonic Crystal Fibres**

The propagation of ultrashort pulses of light in optical fibre has proved to be a very efficient method of 'squeezing' the quantum properties of light. Squeezing means the reduction of quantum fluctuations in one variable below the standard quantum limit and has application in precision measurement and entanglement generation.

Photonic crystal, or microstructured, fibres are made from ordinary silica, but have a pattern of holes built in. Such fibres can be tailor-made to radically alter the propagation modes of the light, producing, for example, much larger effective nonlinearities (all the better for squeezing).

In this project, you will study the quantum propagation of pulses in photonic crystal fibres (using quantum-noise simulation methods) in order to determine the optimum quantum squeezing. Your results will be of interest to researchers who are now implementing squeezing experiments with microstructured fibre.

Areas: quantum physics, computational physics, optics

**Precision Measurement with ultracold atoms in a double-well potential**

Bose-Einstein condensates in a double-well potentials have been used as a relatively simple system in which to study the quantum many-body physics of ultracold atoms, in particular the interplay of quantum tunnelling and particle interactions.

This project will investigate the use of a BEC in a double-well potential for quantum squeezing and interferometry. The two-mode approximation will be used to describe essential dynamical features of tunnelling between the two wells and self-trapping. Particular aspects to be investigated include: timescales required to form the optically squeezed or entangled states, and the effect of residual interactions in some recently proposed schemes.

Areas: quantum measurement, Bose-Einstein condensates