Low-dimensional quantum gases represent examples of strongly correlated quantum systems and are the subject of intense theoretical and experimental activity in many areas of physics. These are relevant to the ACQAO experimental programs in the areas of interferometry in atom chips with Bose or Fermi gases (SUT), as well as to future atom-counting experiments with metastable Helium (ANU).

In 2005, we have made further progress in the studies of atom correlations in one-dimensional (1D) Bose gases [1]. We have calculated the density profiles and density correlation functions of a harmonically trapped (nonuniform) 1D Bose gas, using the exact finite-temperature solutions for the uniform case and applying a local density approximation. The results are valid for a trapping potential which is slowly varying relative to a correlation length. They allow a direct experimental test of the transition from the weak coupling Gross-Pitaevskii regime to the strong coupling, “fermionic” Tonks-Girardeau regime. We have also computed the average two-particle correlation \( g^{(2)} \) which characterizes the bulk properties of the sample, and found that it can be well approximated by the more readily calculated local pair correlation in the trap center, \( g^{(2)}(0,0) \).

The figure on the left shows \( g^{(2)}(0,0) \) (solid lines) and \( \bar{g}^{(2)} \) (dashed lines) as a function of the interaction parameter \( \gamma(0) \), for four different values of a dimensionless temperature parameter \( t \). This result is of practical importance as it gives a direct justification of the analysis performed in [2] where the results of the measurements in a bulk nonuniform sample have been compared with theoretical predictions for the local pair correlation in a uniform gas [3]. More recent experiments in D. Weiss’s group [4] are also in excellent agreement with our theoretical results.

In addition, in view of the rapid growth in ultra-cold fermion physics, we have commenced a program of investigating the signature of the fermionic Mott-insulator transition in a 1D optical lattice [5]. With optical lattices, a harmonic potential is necessary to prevent the atoms from escaping, so that the Mott-insulator phase is restricted to an insulator domain at the center of the trap, and coexists with two compressible metallic wings. In this work, we show that collective oscillations of the atomic mass density, an indicator of compressibility, can be utilized to monitor the emergence of the Mott-insulator phase. We consider a zero temperature, one-dimensional Hubbard model with a harmonic potential, as a model of an ultra-cold two-component fermionic atomic cloud in a deep optical lattice with strong radial and weak axial confinement. Based on the exact solution of the homogeneous 1D Hubbard model, together with the local density approximation, we calculate the density profile of the cloud as functions of a characteristic filling factor and coupling constant. This leads to a generic phase diagram including a metallic phase and a Mott-insulator phase. We then investigate the low-energy collective density oscillations of the cloud in different phases using Luttinger liquid theory, which describes long wavelength hydrodynamic behaviour. We predict a sharp dip in all collective mode frequencies in the vicinity of the phase boundary, giving a clear signature of the Mott metal-insulator transition.

References