Ultracold atoms for simulation of many body quantum systems

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Abstract. Feynman famously proposed simulating quantum physics using other, better controlled, quantum systems. This vision is now a reality within the realm of ultracold atomic physics. We discuss how these systems can be used to simulate many body physics, concentrating the Berezinskii-Kosterlitz-Thouless transition in 2D physics and the role of disorder.

1. Introduction
It took 70 years from the prediction of Bose-Einstein condensation (BEC) in 1925 to the experimental realization [1] in 1995 in ultracold atomic gases. Whilst phenomena such as superfluidity in liquid helium, superconductivity of Cooper Pairs and even the macroscopic occupation of an individual cavity mode in the laser are all related to BEC, the experiments in 1995 where the first to directly show this condensation directly. In time of flight images – where the trapped cloud of atoms are allowed to expand and are then detected via an absorption image – the momentum distribution of the atoms is directly inferred showing the macroscopic occupation of the lowest momentum state.

The first experiments were then an exercise in characterization and developing an understanding of wave interference in these new systems. We were involved in a large part in the characterization of collective excitations at finite temperatures in these early systems, with the key characteristic being the demonstration of precision control both over internal and external degrees of freedom. For example, experiments by Debbie Jin [2] explored the temperature dependence of the collective excitation spectrum of early condensates revealing anomalous high temperature (here “high” means a hundred nano-Kelvin or so) shifts in the monopole and quadrupole modes. The theory to explain this, developed by us[3], involved a detailed understanding of the many body scattering properties of dilute gases in the presence of a condensate as well as the interplay between the dynamics of the condensate and that of the thermal atoms. The latter was characterized in a phenomenological manner by Zaremba [4] and co-workers and later by us in a microscopic treatment [5] based upon a Beliaev [6] type approach.

These early examples formed the foundation for studies of coherence including interference phenomena [7], over which it is now hard to believe there was such controversy and early demonstrations of matter wave beams, or atom lasers [8] as was the buzzword. Applications of matter wave interference and the atom laser have begun to find practical applications in the realms of inertial guidance [9–11] and even gravity sensing [12, 13] where the massive nature of the atoms yields an advantage over optical equivalents, but we believe it is in the field of quantum simulation that cold atoms will play their most important role.
2. Cold gases for quantum simulation

The ultracold gases were saved from being a purely demonstration experiment by the advent of further control over the inter-particle interactions through the use of so-called Feshbach [14] resonances. These resonances vary the relative energy between open and closed channels in two-particle scattering by the imposition of a uniform magnetic field. The differing Zeeman shift for the different levels then leads to a change in the position of the last bound state, varying the effective s-wave scattering length. Interactions could therefore be tuned from attractive through zero (non-interacting) to repulsive, including also the divergent scattering length in the unitary regime.

Optical lattices [15] were then introduced into the experimentalist’s arsenal of techniques. This uses two counter-propagating laser beams to create a standing wave. The ac Stark shift then leads to an effective harmonic potential for the atoms. One, two and three dimensional lattices can be formed in this manner together with more exotic potentials through the use of spatial light modulation techniques. By making one or more of these lattices very strong, with tight confinement in that direction, even the dimension of the system can be manipulated to create two-dimensional sheets, one dimensional wires, or dot-like structures.

3. Simulation of two-dimensional systems

Beautiful experiments by the group of Jean Dalibard in Paris then used optical lattices to produce two-dimensional sheets [16] of degenerate Bose gases. Theory of the non-interacting Bose gas shows that there is no BEC transition in the uniform two-dimensional Bose gas, but predicts a finite degeneracy temperature for a harmonically trapped gas – like those in the Dalibard experiments. The interacting two-dimensional gas can however undergo a superfluid phase transition to the so-called Berezinskii-Kosterlitz-Thouless (BKT) Phase. In this state fluctuations in the form of thermally activated vortices are bound in to vortex-antivortex pairs. Whilst global phase coherence – the characteristic of BEC – is destroyed, the system retains a local order that leads to a superfluid phase. The superfluid phase is then destroyed at higher temperatures by the vortex-antivortex pairs unbinding. The critical temperature is therefore related to the interparticle interactions. Cross over from the BEC to BKT phase and through to the thermal phase was investigated and characterized in these experiments and supporting theoretical work from ourselves[17–20] and others at Otago [21–23] as well as elsewhere [24].

Whilst this area is especially timely due to the recent award of the 2016 Nobel Prize in Physics to Kosterlitz and Thouless, as well as Duncan Haldane (also two-dimensional physics), much has been added to our understanding of two-dimensional physics in finite systems by studies in the cold gases. This continues to be the case, not least through the new experiments by Perrin reported elsewhere in this volume.

4. Disordered systems

The next piece in the quantum simulation jigsaw was the introduction of disorder. Disorder can be introduced in to a cold atom system via either a new, weak optical lattice incommensurate [25] with the primary optical lattice or through laser speckle [26]. The former, while not strictly disorder, provides an effectively random shift to the bottoms of the primary lattice potential. Laser speckle consists of light shone through a diffusive plate to provide a random optical potential shift. Both mechanisms have been used to demonstrate localization and effective superfluid to insulating phase transitions in ultracold gas systems. Work is now ongoing investigating the effects of disorder in ultracold gases with the hope of shedding light on the role of disorder in more complicated solid state systems.

One of the beauties of the cold atom systems, as stated above, is the ability to tune interactions. The interplay between localizing effects of disorder and the role of inter-particle interactions is a fascinating one and many body localization [27] is now one of the fashionable areas of cold atom research. Our main area of focus however has been on the role of magnetic fields in the presence of disorder. Simple arguments can be used to highlight how time reversal symmetry leads to enhanced localization in the presence of disorder. The imposition of a magnetic field breaks time reversal
symmetry and hence suppresses localization leading to negative magnetoresistance. We have demonstrated theoretically [28] how this may be achieved in ultracold atomic gases, but how does one simulate a charged gas in a magnetic field using neutral atoms?

5. Synthetic gauge fields

The final element to be introduced to our world of ultracold atomic emulation of solid state systems are gauge fields. These ultracold atomic systems are by definition uncharged. They therefore do not couple to electric or magnetic fields in the sense of, say, electrons in solids. We need to introduce effective potentials in to the system Hamiltonian via other means. For example rotating the system introduces a term in the kinetic energy which mirrors the effects of a magnetic field. Quantised vortices and vortex lattices have been observed using rotation. Analogues of the integer and fractional quantum Hall effect based upon rotation have been proposed but are limited. Rotation also introduces an effective centripetal force which, at a rotation frequency equal to that of the harmonic trap confinement leads to instability of the gas through failure of the trapping.

A scheme first implemented by Ian Spielman’s group at NIST used a Raman scheme to couple hyperfine states [29] in a spatially dependent manner. This lead to a minimum in the kinetic energy term centred at a momentum $p \neq 0$. Effectively this introduces a spatially dependent vector potential $A$ and hence a synthetic magnetic field. Spielman was able to demonstrate that implementing this coupling led to vortices in his condensate analogous to rotation. This scheme has since been extended to other gauge fields [30, 31] including non-abelian fields and also spin-orbit coupling.

6. Conclusions

In this very brief review we have concentrated on our own contributions to the field as this is what we talked about in Novosibirsk. I would however like to point the interested reader to the much better review article in *Nature Physics* [32].

What we would like to stress though is that ultracold atoms really offer a platform for studying many phenomena from solid state physics. They provide excellent control, through precision laser and atomic physics, overall system parameters. Model Hamiltonians can really be engineered in the spirit of Richard Feynman’s vision [33] of quantum simulation from the 1980s.

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