Quantum Gases in Synthetic Gauge Fields

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Fellow: Dr Ryan Barnett, Dept of Mathematics, Imperial College London
`http://wwwf.imperial.ac.uk/~rlbarnet/`

Introduction. During 2014-2018, our research has been generously supported, in part, by the Career Integration Grant "QUANTUM GASES IN SYNTHETIC GAUGE FIELDS". The overarching objective of this CIG was to understand at the fundamental level how ultracold atomic gases collectively organise under the presence of external synthetic gauge fields. Progress in this area will help the community to better understand topological phases of matter [1]. Furthermore, it might also form the basis of future quantum technological applications such as forming the hardware for quantum computers. Much of the work carried out during this CIG is motivated and/or inspired by recent experimental progress in realising synthetic gauge fields in ultracold matter which has been rapid in recent years (see, for example, the recent review [2] and references therein). Below we provide a brief summary of the results from the four main areas of the project.

Edge-state dynamics of bosons in Bloch bands with nontrivial topology. Among the top-priority applications for synthetic gauge fields is to engineer Bloch bands with non-trivial topology, such as Chern bands. Such systems typically possess robust states located on the edges of the system, which are protected by the topology of the bulk system. However, edge modes typically play an inessential role in the near-equilibrium properties of bosonic systems, since bosons will generally populate the lowest-energy single-particle states while leaving the higher-energy edge modes empty. This is in stark contrast to fermionic systems where edge modes are responsible for important effects such as quantum Hall conductivity.

In work prior to this grant, it was shown that edge modes of a certain one-dimensional system can be controllably populated by a quantum quench [3]. During the CIG we showed how to extend these results to vastly richer two-dimensional systems [4]. Unlike the one-dimensional system, the quenching induces a current along the boundary of the two-dimensional system. We also showed that harmonic traps (which are most common in experiments) are not necessarily detrimental for these edge states [5]. Finally, in a spin-off work we completed a project concerning Majorana edge states in interacting Fermion systems [6].

Quantum control of spinor condensate dynamics. This project involves, in part, a collaboration with the experimental group of Paul Lett at NIST (Gaithersburg, Maryland, USA). This group has an experimental system of a sodium spinor condensate which is tightly confined such that, in many cases, the spatial degrees of freedom are frozen out and the internal spin of the atoms provide the relevant degrees of freedom.

In [7] we showed that a collection of spin-two atoms in the regime of tight confinement can be described by a quantum rotor model which can offer a number of simplifications over previous treatments. We also theoretically described a spin-sensitive amplifier (a crucial component for the so-called SU(1,1) interferometer) in a paper containing both experiment and theory [8].

Bosons in flat-band lattice systems. The goal of this project was to address how many-particle systems of bosons organise themselves in lattices which yield flat-bands (i.e. bands which have no dispersion). For such systems, the kinetic energy is macroscopically degenerate and so interactions are necessarily of central importance. The so-called dice lattice under an external gauge field offers an example of a flat band model. This project was aimed at addressing how interacting bosons collectively organise themselves under the presence of the gauge field.

In this project we focused on the regime where Gross-Pitaevskii mean field theory is valid.

By integrating over quantum and thermal fluctuations, we found that a unique ground state is selected through the mechanism of order-by-disorder [9].

Computational treatment of mean field bosons under external gauge fields. In this area, we developed a scheme that is able to describe infinite superfluids under a uniform external gauge field [10]. This method is able to describe pristine infinite vortex lattice configurations with great accuracy. In a follow-up work [11] we described how the method can be extended to treat multi-component superfluids including those with Rashba spin-orbit coupling. In the same work, we obtained a phase diagram showing the possible vortex lattice configurations in binary mixtures of superfluids.

Conclusion This CIG has proven to be instrumental for integrating the Fellow into the European research community. During the course of the grant, numerous collaborations have been established, and many exciting directions for future work has been established. Furthermore, two students have been awarded PhDs under the guidance of the fellow for work pursuing the objectives of this CIG.

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