Quantum Simulation of Fermionic Matter at the Single-Atom Level

PhD Project

This thesis will be devoted to atom-based quantum simulation of strongly-interacting fermionic quantum matter, with single-atom imaging and control capabilities. Two specific systems will be explored (i) the Unitary Fermi gas and (ii) quantum Hall fluids. It will take place on a cold atom apparatus within the Fermi Gases Team at Laboratoire Kastler Brossel (LKB) under the supervision of Tarik Yefsah and Fabrice Gerbier.

Scientific Context

From the promise of exponentially faster computers, new ways to transmit and store information, and vastly improved sensing capabilities, quantum science has become an extremely active area of research, providing a wide range of platforms, each with its particular strength. For example, photons have already made quantum cryptography possible, superconducting qubits and trapped atoms/ions are commercially pursued for universal digital computing, NV centers promise sensing with unprecedented spatial resolution. With quantum gases of ultracold atoms and molecules, experiments have had tremendous success in tackling quantum many-body problems, where unexpected and qualitatively new phenomena can emerge. These problems are notoriously complex owing to the large number of interacting particles, strong interactions, disorder, or nonlinear dynamics. This is the general context of this PhD work, which will focus on atom-based quantum simulation of strongly-interacting fermionic quantum matter.

Strongly-correlated fermions are ubiquitous in nature, from the quark-gluon plasma of the early universe to neutron stars found in outer space, they lie as well at the heart of many modern materials such as high-temperature superconductors, colossal magneto-resistance devices or graphene. While being a pressing issue covering a wide fundamental and technological scope, the understanding of strongly-correlated fermions constitutes a serious challenge of modern physics, which is often hindered by the complexity of the host systems themselves. The contribution of ultracold gas experiments in this outstanding quest resides in the ability to set fermions in a well-characterized environment, where one can add a single ingredient at a time (spin mixture, interactions, lattice, etc) with a high degree of control, allowing for an incremental complexity, which represents an ideal playground for a direct comparison to many-body theories.

Quantum gas microscopy

One of the main assets of the new generation experiment where this PhD will be performed is the ability to take images of a quantum gas with single-atom resolution 1. This single-atom imaging technique consists in pinning the atoms in space using a deep optical lattice while exposing them to a cooling laser light. During this cooling process, atoms absorb and re-emit photons that are collected by a high-resolution objective to create an image of the atoms on a CCD Camera. Such a quantum gas microscope is unique in France – and one of three in Europe – and offers the possibility to probe the microscopic properties of strongly interacting Fermi gases at an unprecedented level. Importantly, while quantum gas microscopes have already been developed by a few groups for bosonic [1, 2] and fermionic atoms [3, 4, 5, 6], they have mostly been used to probe lattice (Hubbard) physics. In this PhD, we will utilize this tool to probe Fermi gases in continuous space for the first time.

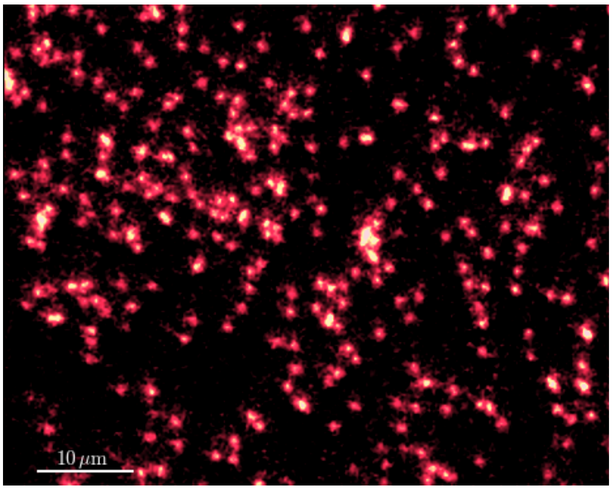

Figure 1: **Single-atom imaging of an ultracold ^{6}Li cloud (LKB experiment).** The quantum gas microscope is a powerful tool until now devoted to the study of lattice physics. Our experiment is designed to apply it to continuous gases: after preparing the cloud in a given state of matter, the atoms are suddenly frozen in a deep optical network and exposed to near-resonant light. On this image, each luminous point (in red) indicates the presence of an atom.

The Unitary Fermi Gas

The system of interest here is an assembly of spin–1/2 particles with tunable interactions and spin population. In practice, the two spin states are two different hyperfine states of ^{6}Li. The inter-particle interactions, which are characterized by the scattering length a, can be tuned experimentally by means of a Feshbach resonance. At the resonance, where $a \to \infty$, the interactions are as strong as allowed by quantum mechanics and the systems strongly correlated. The system is referred to as the Unitary Fermi gas and represents one of the hardest challenges of quantum many-body physics.

One of the primary goals of this PhD work is to take advantage of the single-atom detection to probe spin-correlation functions in the Unitary regime, which are beyond the capabilities of existing experiments or theoretical methods. This type of measurements will help gain a unique insight on strongly-correlated fermionic quantum matter.

Quantum Hall Fluids of Neutral Particles

The second topic of this PhD project is the exploration of topological matter, namely, quantum Hall (QH) states. In the past twenty years, several experimental and theoretical efforts were made for the creation of topologically non-trivial states in ultracold atomic systems.

We will develop a new scheme to realize QH states and probe directly their spatial distribution with single-atom resolution. Our experimental strategy is to set ultracold gases in rotation. The resulting Coriolis force in the rotating frame mimics the Lorentz force felt by the electrons and gives access to the physics of Landau levels despite the electrical neutrality of atoms. We will combine this well-established method with the use of single-atom imaging and a Feshbach resonance that allows dynamic tuning of the strength of the inter-atomic interactions. The combination of all three ingredients will allow us to reach, probe, and manipulate a variety of correlated QH states.

References

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