Lithium lab

Non-equilibrium Relaxation in Many-Body Quantum Systems

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Machine learning for atom recognition

In fluorescence imaging, photons scattered by atoms are collected by the imaging optics and detected by a highly sensitive electron-multiplying charge coupled device (EMCCD) camera. An atom's signal is recorded in the image as a group of clustered photons. At very low densities where the particles have large separations and a low chance of spatially overlapping, particle recognition is trivial if given detection images with good signal to noise ratio, and the fidelity of detecting each single atom can be near 100%. The task becomes complex and challenging for intermediate densities where particles are often found close to each other, and basic image processing such as applying a low pass filter does not suffice to identify each particle with well resolved positions.

This project aims to develop a procedure to train machines to specific experiments (rubidium 87 with time-of-flight detection and isotropic fluorescence, or lithium 6 with in situ detection and fluorescence with dipole radiation pattern). A simulation package for fluorescence imaging of atoms in quantum gas experiments has been developed, which takes into account detuning and saturation effect as well as aberration of the imaging optics and the response of the EMCCD camera. The simulation results can provide a large amount of training data for the machine learning task. The trained machined will then serve to analyse experimental images. In this project we will consider, implement, and compare some existing image processing techniques such as clustering and convolutional neural network, and seek to establish an effective set of operations to be optimized by the learning algorithm.

Accordion superlattice for optically resolvable 1D gases

We aim to realize and implement a versatile optical accordion lattice setup capable of various trapping and manipulation procedures. The scheme requires careful design for stability, as well as feedback control for lattice phase correction.

The design is based on a so-called equal-path interferometer, which provides passive long term phase stability. In addition the beam crossing angle is determined by the position of the input laser beam. By scanning the input beam with an acousto-optic deflector (AOD), the optical lattice potential can be dynamically controlled, and multiple lattices of different periods can be applied simultaneously.

The scheme will allow the experiment to easily trap ultracold atoms in a single layer of the optical lattice, to vary the spatial separation and the strength of confinement for the trapped gases. It is also possible to transfer atoms from a longer-period to a shorter-period lattice trap, resulting in tightly confined 1D gases separated by empty lattice sites, allowing fluorescence imaging with higher signal while maintaining the ability to resolve single systems.

Designing versatile RF drivers for acousto-optic devices

Acousto-optic modulators and deflectors are devices widely used for laser switching, frequency modulation, and intensity control purposes, and are essential for cold atom experiments. In this project we will develop a new design for an analog RF driver for acousto-optic devices with the options to precisely stabilize the RF output to a frequency or to dynamically control the frequency, or to combine with an external source from for example, an arbitrary waveform generator. The project student will learn basic RF electronics and mechanical design.

Light source for tailored optical potential

For shaping arbitrary optical potentials, for instance to produce a flattened potential profile or to dynamically excite quantum gases, the availability of high optical intensity and the absence of interferences are desired. For this purpose, we will characterize and compare various light sources for the application of the digital-micromirror-device (DMD), and explore the techniques to eliminate speckles.

Ferromagnetic transition in two-dimensional Fermi gas

Itinerant ferromagnetic transition is predicted by the Stoner model, when the interaction energy dominates over the kinetic energy of a Fermi gas consisting of two spin states. The experimental confirmation of the magnetic transition in a gas free fermions has been hindered by limited optical resolution compared to the expected initial domain sizes of the magnetic state, the degradation of signal due to imaging through a 3D cloud. In addition at strong interaction close to a Feshbach resonance, the formation of molecules becomes dominant and makes the magnetic state unstable.

In a 2D Fermi gas, the itinerant ferromagnetic transition is expected to be a first-order transition, as opposed to the second-order transition in 3D. This means complete spin separation upon the transition is anticipated, making the detection more feasible and the rate of molecule formation reduced. The physics in a 2D gas is scale invariant, allowing the experiment vary the particle density to further suppress molecule formation while being able to access the transition. A 2D Fermi gas is therefore the suitable system for studying the Stoner model. Furthermore, spatially resolving, state sensitive and single-atom sensitive fluorescence imaging can be applied to 2D gases, thereby unambiguously reveal the magnetic domains. Beyond demonstrating the ferromagnetic transition, the competition between the formations of different order parameters (bound molecules or separated spins) can be investigated.

Searching for the FFLO state in 1D spin-imbalanced Fermi gases

The competition and interplay between superfluid and magnetic behaviours is a fundamental question in many-body physics, magnetization (spin polarization) and superfluidity (pairing) being two types of order parameter mutually incompatible. A special situation in fermionic systems with spin imbalance is the exotic **Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) superfluid state** in which the pairs have finite momenta, and the regions of paired fermions with alternating signs of the order parameter are separated by spin-polarized domain walls consisting of majority spins. In this Discovery project we propose to realize experiments with a single layer of 1D array of Fermi gases, where we can directly observe single tubes. We aim to confirm the FFLO state by establishing spatially resolved, local measurements of the superfluid order parameter for 1D Fermi gases. Our experimental approaches include correlation measurements to characterize the superfluid state, to perform molecule projection to realize boson interference and reveal the phase modulation of the order parameter, and to observe phase sensitive tunnelling or a Josephson junction.

Experimental tests for the theory of generalized hydrodynamics

Recently, a significant breakthrough has been made with the advent of the theory of Generalized Hydrodynamics (GHD), enabling the description of large scale dynamics in integrable models using the concept of emergent hydrodynamics (Bertini et al. 2016; Castro-Alvaredo, Doyon, and Yoshimura 2016). Several mechanisms of integrability-breaking and their effect on GHD have been studied theoretically (Bouchoule et al. 2020), and an extension of GHD into the dimensional cross over regime had been formulated (Møller et al. 2021). To date, experimental tests and applications have only had few investigations (Schemmer et al. 2019; Malvania et al. 2020; Cataldini et al. 2022) and are still waiting for in depth studies.

In our system with a trapped array of quasi-1D gases of bosonic lithium molecules, we will perform experimental tests including interaction quench induced dynamics, competing effects for diffusion, searching for higher order corrections to GHD theory (similar to the Navier-Stokes equation), investigating integrability breaking and relaxation rate in Newton's cradle experiments. In addition we wish to explore the emergence of hydrodynamics in new regimes, such as in weakly interacting 1D Fermi gases, described theoretically by the Gaudin-Yang model (Gaudin 1967; Yang 1967; Scopa 2022).

Numerical simulation for time-of-flight expansion in the presence of strong interaction

Time-of-flight (TOF) measurements are widely practiced in quantum gas experiments to observe and characterize momentum profiles, interferences, or excitations and topological defects. The application of matter wave focusing allow accessing the momentum space with short TOF, and more elaborate implementations even make magnification possible.

Experimenting with strongly interacting gases is confronted with the influence on expansion. This concerns whether the observables of interest are preserved through the TOF, and whether phenomena such as universal dynamics can still be characterized. In cases where the effects of interaction cannot be mitigated, and hence the process cannot be considered as ballistic expansion, we aim to understand the role of interaction both qualitatively and quantitatively, to learn how the TOF evolution is modified, and how the information of interest can be retrieved.

Entangled atom pair quantum processor

The vision of this project and its future continuation is to develop an integrated atom optics platform (atomtronics) for quantum experiments based on entangled pairs of ultracold fermions. The dissociation of a diatomic $^6Li_2$ molecule creates nonlocal entanglement between two ^6Li fermions in a pair and implements a deterministic entanglement source. The platform will be capable of (i) highly deterministic and parallel creation of entangled atom pairs with the atoms launched into single-mode atom waveguides, (ii) implementation of arbitrary atom optical operations and (iii) deterministic state-dependent single-atom detection. The arrangement is a building block that can be scaled up by implementing many sites in parallel and in the future connecting them using an integrated atomtronics platform, thus opening up the path towards a new experimental platform for exploring complex quantum tasks.