Low-dimensional Fermi gases

1) Research project

Context and relevance to the Institute objectives: In the context of the quantum technology program, one of the goals of quantum simulation is to identify experimental platforms capable of replicating the properties of model Hamiltonians used in quantum many-body physics. These Hamiltonians are often too complex to be exactly studied analytically or numerically and various technologies, ranging from quantum gases to Rydberg atoms trapped in optical tweezers and electron-polariton condensates, have now reached a level of maturity where they can address some of the long-standing challenges in quantum many-body physics. A milestone in this research is the definitive solution to the celebrated Bertsch's X-Challenge regarding the equation of state of neutron matter that was provided by experiments on ultracold fermions (1).

The success of these approaches relies on the accurate and quantitative certification of the quantum simulator. Indeed, the models used to describe the operation of quantum simulators are often based on approximations and simplifications. These approximations can introduce errors that need to be characterized and minimized to ensure the reliability of the simulation results. However, unlike classical systems, which can be validated through rigorous testing and verification, quantum simulators operate in a regime where conventional theoretical and numerical approaches are no longer tractable. It thus becomes imperative to establish reliable protocols for quantifying the performance and accuracy of these quantum devices.

Scientific objective: During the thesis, we will address this challenge in the case of the **quantum simulation of ultracold attractive fermions in dimensions lower than 3**. From a fundamental standpoint, lower-dimensional ensembles of particles display intriguing properties that bear little resemblance to their 3D counterparts. For instance, due to enhanced quantum fluctuations, they cannot sustain long-range order, and in 2D superfluidity is driven by the formation of bound pairs of topological excitations. Similarly, strong geometric constraints in 1D prevent relaxation towards true thermal equilibrium, and steady-state properties of these systems are described within the framework of the Generalized Gibbs Ensemble theory. Low-dimensional systems are also predicted to host exotic states, such as Majorana fermions, which have been proposed as potential platforms for the realization of topologically protected quantum information processing devices.

Methodology and Tentative program for the PhD work: The PhD project is centered on the experimental study of this problem. The PhD candidate will join the Fermix group and will be in charge of the operation of 40K machine that is dedicated to the manipulation of fermionic potassium and on which quasi-1D fermionic samples have recently been realized (2). Data analysis and modeling of the experimental results will be performed in collaboration with Giuliano Orso at MPQ.

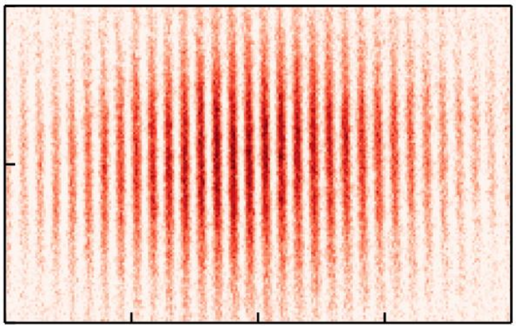

Figure 1: in situ picture of an array of individual tubes obtained on ENS 40K experiment. The distance between tubes is 2.5µm. The Equation of state of strongly correlated attractive fermions can be measured from similar profiles, and the knowledge of the trapping potential (2).

1) ***Measurement of the equation of state***: we will determine experimentally the equation of state of a quasi-low-D gas of potassium close to a Feshbach resonance. This technique is based on the analysis of the density profile of the cloud (1) (3) and a key advantage of our experimental setup is the possibility to probe arrays of individual

tubes or planes. We will vary the temperature, the interaction strength and the confinement. Specifically, we will delineate the parameter range where the system's behavior exhibits universality and where the combined effects of the latter two parameters can be effectively captured by a single 1D or 2D scattering length. Additionally, we will delve into the implications of spin polarization, with particular focus on the highly polarized regime where minority spin atoms exhibit impurity-like behavior.

2) ***Radiofrequency spectroscopy***: radiofrequency spectroscopy is a powerful tool for the study of the nature of low-lying excitations (4). In particular, we will use it in the quasi-1D case to determine their quasi-particle nature and study the onset of a Luttinger Liquid regime.
3) **Effective quasi-low D models**: We will first benchmark our experimental results two existing theoretical calculations in pure 1D and 2D in order to identify the range of parameter where the low-dimensional model provides a good description of the system. In the regime of strong correlations these experimental results will lay the ground for the search of the proper effective theory describing the behaviour of a quasi-low-D system. In particular we will focus on the determination of the low-energy sector were even in the strongly interacting regime, low-lying excitations should remain truly 1D or 2D.

2) Supervision

The PhD work will be supervised by Frédéric Chevy who is an expert in the theoretical and experimental aspects of quantum and classical fluids. His research interests encompass a wide range of topics, including the study of strongly correlated fermionic matter or quantum impurity problems. He recently started exploring the interplay between confinement and quantum correlations in quasi-low dimensional quantum matter (2) (5). He has supervised and co-supervised 24 PhD candidates.
The modelling and simulation aspects of the project will be co-supervised by Giuliano Orso from MPQ who is an expert in 1D systems and advanced numerical methods for strongly correlated systems (6). GO and FC have an already established collaboration that was recently at the origin of one article (5) and another one in preparation. This joint PhD supervision would then be the opportunity to reinforce the interactions between the two groups.

3) References:

1. *Exploring the thermodynamics of a universal Fermi gas.* **Nascimbène, S., et al.** 2010, Nature, Vol. 463, p. 1057.
2. *In Situ Thermometry of Fermionic Cold-Atom Quantum Wires.* **De Daniloff, C., et al.** 2021, Phys. Rev. Lett. , Vol. 127, p. 113602.
3. *The equation of state of a low-temperature Fermi gas with tunable interactions.* **Navon N., Nascimbène S., Chevy F., Salomon C.** 2010, Science, Vol. 328, p. 729.
4. *Observation of the pairing gap in a strongly interacting Fermi gas.* **Chin, C., et al.** 2004, Science, Vol. 305, p. 1128.
5. *Achieving one-dimensionality with attractive fermions.* **Chevy, F. et Orso, G.** 2023, Vol. 107, p. 043317.
6. *Attractive Fermi gases with unequal spin populations in highly elongated traps.* **Orso, G.** 2007, Phys. Rev. Lett., Vol. 98, p. 070402.