Research Project

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INTRODUCTION

The study of fermionic many-body systems is crucial for the understanding of many phenomena, as fermions are the fundamental component of matter. The behaviour of electrons in solid state system or nucleons in atomic nuclei are some examples. However, as the number of particle in the system increases, a theoretical description and numerical simulation are too complicated. In order to understand the behaviour of these systems, Feynman proposed the use of controllable quantum systems as quantum simulators [1]. The high degree of control and manipulation obtained in the last decades on atomic samples makes ultracold quantum gases an ideal candidate for this realization. In particular, strongly interacting gases of ultracold fermionic atoms are perfect platforms for the study of many-body phenomena in the BEC-BCS crossover, allowing to study superfluidity in a Bose-Einstein condensate (BEC) formed by repulsive diatomic molecules, a Bardeen-Cooper-Schrieffer (BCS) regime of attractive atoms and the strongly interacting unitary limit, that has important analogies with *High-Tc* superconductors.

In the development of new quantum technologies, *High-Tc* superconductors play a crucial role for their capability of carrying supercurrents at relatively high temperature and, as *type-II* superconductors, high magnetic field. For field above a critical value H_{c1}, this is achievable with the formation of quantized vortices [2], across which magnetic flux can penetrate in the system. However, the motion of these same vortices is responsable for dissipation [3]. Due to the complexity of this system arising from the interaction of vortices with other vortices and with impurities in the system, the dynamic behaviour of vortex matter is not easily handable by a theoretical side and with conventional numerical simulations. Also, experiment on vortices dynamic in superconductor are not trivial. A quantum simulator is desirable. In the field of bosonic and fermionic atomic superfluids, vortices nucleation have been widely studied. Standard techniques for vortices creation do not permit a control over the created configuration, as the specific position of each vortex is not a priority in most of these works. However, accurate studies on vortices dynamics and interaction requires the possibility to create vortices in a arbitrary and deterministically reproducible configuration in a on-demand potential. This can represent a useful toll for quantum simulating the dissipative behaviour of the vortex dynamics in an arbitrary impurities landscape, and of the transport properties in a pinned-vortex configuration, whose understanding is of strongly interest towards the realization of high-performance superconductors.

RESEARCH PROJECT

In my Ph.D. project, I propose to use a quasi two-dimensional strongly correlated Fermi gas to create a versatile toolbox for the study of solid state phenomena, by using well corroborated techniques and adopting unexplored ones, in order to create an accessible quantum simulator with remote control of the experimental setup. In particular, I will study the dynamic behaviour of vortices in arbitrary landscape, and their pinning in presence of artificial impurities in a strongly correlated fermionic superfluid across the BEC-BCS crossover. I will be able to add vortex in the system one-by-one, controlling their individual position in analogy with Rydberg atoms experiment. I propose to realize my project at LENS, in the lithium laboratory under the supervision of Dr. Giacomo Roati. In this laboratory, strongly correlated ultracold Fermi gases are obtained applying techniques of laser and evaporative cooling on the $6Li$ atom, creating a balanced mixture of the two lowest hyperfine spin level of this atom, with a quasi homogeneous density in the horizontal plane. The presence of an objective with numerical aperture NA=0.4 allows to imaging the sample and, with the use of a Digital Micromirror Device (DMD), to create arbitrary optical potential with sub-micron resolution. With the use of the DMD is possible to realize homogeneous as well as on-demand shape ultracold Fermi gases, and to engineering the presence of imperfections in the system, with an high control on their number, position and intensity.

- In the first part of my Ph.D. I will study dissipation in vortices dynamics in fermionic superfluids versus the temperature of the system. In order to realize this type of study, I will create vortices dipoles (namely a couple of vortex and antivortex) in the system with the chopstick method [5] by creating two moving impurities in the system with the DMD. This method, that has been already demonstrated in this experimental apparatus [4], allows to create vortex dipoles (namely a couple of vortex and antivortex) with a high control over their position and velocity, that are reproducible in a deterministic way. In particular a couple of vortex and anti-vortex can be created with a well defined separation *d* and velocity. I will study the dynamic of the vortex dipole, that allows to observe dissipative effects, tracking the evolution of the vortices position. The homogeneity of the system allows to characterize the energy of the dipole from the vortex separation. Previous observations [4] show a more dissipative behaviour in the BCS regime, that can be explained with the presence of quasiparticles bound state in the vortex core [6], known as Andreev state. Moreover, theoretical works [7] underline the importance of temperature in the dissipative dynamic, arising from a change in the occupation of the Andreev states. I will therefore study the dissipative effects of this bound states in the vortex core on the dynamics of the dipole for different temperature, expanding the results obtained in [4] for the lowest temperature achievable in the system. In order to do this, I will analyze the evolution of the vortex-antivortex separation in time by imaging the position of the vortices. Usually, experiment on 6Li ultracold quantum gases are performed with a balanced population of the two lower hyperfine states. However in the experimental setup, with an already installed antenna, is possible to couple the two state creating an imbalance in their population. In the BCS regime, superfluidity arises from the formation of Cooper pairs of two particles with different spin. Therefore, in a spin imbalance configuration some atoms are uncoupled and costituite the non superfluid component of the system. Theoretical works suggest that the normal part of the system fills the core of a vortex and introduces additional dissipation in the dynamic. Therefore, I will repeat the experiment with a spin imbalance system to study the richer dissipative effects arising from this configuration

- In the second part of my Ph.D. I will focus on the study of interaction of vortices and sound waves. The interplay between sound and quantized vortices has been studied in ultracold quantum gases, by the observation of waves emission from an accelerating vortex [8], or by emission of sound after a vortex-antivortex annichilation [4]. I will create vortex dipoles in an homogeneous system with the same method discussed above. At the same time, I will create sound waves in the system by periodically move the wall created by the DMD that ensures the confinement. With this procedure I will be able to study the scattering of a plane wave against a vortex dipole across the BEC-BCS crossover, pointing out the possible differences for different regime of superfluidity. In particular, the structure of vortex core can influence the scattering process, with the possible excitation of Andreev bound states in the BCS and unitary superfluid with the absorption of phonons. By realizing a homogeneous squared-shape confinement as in Fig. 1b, I will create plane waves by perturbing the position of one single side. With this procedure, I will be able to study the scattering process for different relative angles between the vortex dipole velocity and the wave vector of the sound wave.
- Finally, I will study vortex dynamics and pinning in an engineered impurities landscape. In *High-Tc* superconductors at *T* = 0K, magnetic field above H_{c1} can penetrate in the system, giving rise to the Abrikosov vortex lattice phase [9], in which vortices are arranged in a crystalline structure. However, this state is not exactly superconductive as vortices can move when a current is excited in the system [10]. The presence of disordered impurities can destroy the lattice phase because vortices can be pinned by them, giving rise to a vortex-glass phase, in which the resistivity of the system is restored [9]. In opposition to what happens in superconductive system, where the presence of impurities is not controllable, in our case, repulsive optical defects in the system are created with the DMD, giving us the possibility to engineer the impurities landscape. This will give us the opportunity to explore these different vortices phases. In this context, I propose to study the effect of a disordered set of defects on the stability of currents in a ring-shaped superfluids. With the use of the DMD, I will created a toroidal superfluid. I will excite supercurrents with circulation of the velocity along the ring in the system using a phase imprinting method [11], that has been already deeply tested in this laboratory. I will detect the circulation state of the system by an interferometric measure between the ring and a inner disk that I will add to the system. Previous studies showed the instability of currents above a critical circulation state against the presence of an obstacle whose intensity is on the order of the chemical potential [12]. In particular, the decay of the current arises with the nucleation of vortices from the inner side of the ring, and a complete crossing along the ring. Creating a disordered landscape of defect I will study the possibility to obtain a non dissipative system, for the vortex pinning in analogy with the vortex glass-phase. It is important to notice that the intensity of the potential needed to pin a vortex in this system is well below the chemical potential. Therefore, the superfluid flow is not affected by the presence of this impurities. I will study the time evolution of the circulation state of the system in the single obstacle case and when the disorder landscape is added to the system.

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