Ultracold atomic systems with disorder and long-range interactions

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Ultracold quantum gases have proven to be ideal systems for observing intriguing many-body quantum effects usually encountered in condensed matter physics. Advanced experimental techniques allow an extremely high degree of control over these systems, bringing them at the frontier of modern quantum physics.
Although quantum gases are very dilute systems with respect to solid state systems, most of their properties are governed by interactions between particles. Typically, in the ultracold regime characteristics of quantum gases (temperatures in the nanoKelvin regime), only s-wave scattering between particles can take place. This allows to replace the real interaction potential by a pseudo-potential which is short-range (contact potential), isotropic and characterized by a single parameter, the s-wave scattering length.

An interesting scenario appears in systems where these interactions exist in combination to other features, such as a disordered environment and/or long-range interactions between particles.
The interplay of interactions and disorder in quantum degenerate systems is a very general issue of solid state physics concerning, for instance, thin-film superconductors and superfluid helium in porous media. On one side, disorder tends to localize non-interacting quantum particles, on the other, weak repulsive interactions lead to delocalization and superfluidity.
If the particles have a permanent electric or magnetic dipole moment, dipole-dipole interactions take place between them. The distinguishing feature of these interactions is their long-range and anistropic character. Dipolar interactions account for many physically and biologically significant phenomena, ranging from novel phases appearing at low temperatures in quantum many-body systems, liquid crystals and ferrofluids in soft condensed matter physics to the mechanism underlaying protein folding.

My PhD project developes in the framework of a scientific collaboration between two leading European research groups in the field of quantum simulation of strongly correlated many-body systems with ultracold atoms: the group of Prof. Giovanni Modugno at LENS, in Florence, and the group of Prof. Francesca Ferlaino at the University of Innsbruck (Innsbruck, Austria). The first part of my PhD has been carried out in the group of Prof. Modugno, while in the second part (starting from May, 2016) I will work in the group of Prof. Ferlaino.
The long-term goal of the Florence experiment is to explore the phase diagram of a Bose-Einstein condensate of Potassium atoms in presence of controllable interactions and disorder. With this system it will be possible to investigate several phenomena concerning disordered quantum many-body systems, such as three-dimensional Anderson localization [1] and the open problem of many-body localization. My contribution to this experiment has been at the very starting step and consisted in the design and construction of a new vacuum apparatus necessary to produce the Bose-Einstein condensate of Potassium. The vacuum system will be later integrated with proper laser sources already existent at LENS, and the whole setup should be ready for work approximately in one year.
In Innsbruck I will take part in an already running experiment, where strongly magnetic Erbium atoms with long-range dipole-dipole interactions are used. In this kind of novel systems, the competition between the dipolar interaction and the contact interaction gives rise to many attractive phenomena. One idea for my project is to start from the exploration of the quantum phases of a dipolar gas on a lattice [2], and then move towards the realization of a lattice spin model with dipole-dipole interactions, in order to investigate quantum magnetism phenomena. Another study could involve disorder in dipolar systems. This latter project would bring an interesting connection to the Florence experiment.

References:

[1] Semeghini et al., *Nature Physics* **11**, 554–559 (2015)

[2] Baier et al., *Science* **352**, 201-205 (2016)