Quantum simulation of topological states with ultracold fermions

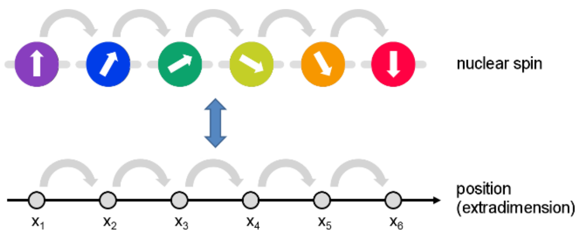
Lorenzo Franchi

Supervisor: Prof. Leonardo Fallani

My research proposal joins the field of quantum simulation with ultracold atoms, which is one of the most promising applications in the field of quantum technologies. In the last decade, experiments with optical lattices have shown that ultracold atoms can be used as a very versatile and tunable platform to "quantum simulate" the behavior of condensed-matter models, giving valuable insight e.g. for the study of the metal-insulator transition or the effects of disorder on a conducting system. An open challenge in this field of research is raised by the simulation of topological states of matter, induced e.g. by external gauge fields (such as a magnetic field for charged particles, as in the quantum Hall effect) or by spin-orbit coupling.

This research project is about the experimental investigation of ultracold fermionic systems based on the synthesis of new forms of interaction by the use of laser light. In particular, I propose to investigate new forms of spin-orbit coupling in which the spin of the particles is locked to their momentum by the use of appropriate laser transitions. Recently, this type of spin-orbit interaction has been implemented using the inner degrees of freedom of ^{173}Yb atoms [1,2].

1. Spin-orbit coupling in a large-spin system: "Synthetic dimensions".



Due to its non trivial nuclear spin (I=5/2), this atom exhibit a substructure in which each sub-state is characterized by a different nuclear-spin projection. These states can be coupled by a two-photon Raman transition induced by two laser beams with different polarization. The coherent coupling between the spins results in an effective dynamics along a "synthetic dimension": each spin state is mapped onto a discrete position and spin-flip transitions between spin states can be interpreted as a quantum tunneling between different sites of this "synthetic dimension". The momentum transfer in the atom-laser interaction that provides the spin-orbit coupling can be interpreted in terms of a fictitious Lorentz force. This fictitious force can be linked to an extremely intense magnetic field (10^4 T) that can be tuned by changing the laser parameters.

- Investigation of the effects of interactions. Recent theoretical studies [3] suggest the possible appearance of new quantum phases with analogies to fractional quantum Hall states. My research proposes to investigate these new states changing the atom-atom interaction and the other tunable properties of the system.
- Realization of synthetic dimensions with "physical" periodic boundary conditions. The other idea is to induce "physical" periodic boundary conditions along the synthetic dimension by realizing closed-loop Raman couplings. This system can allow to observe experimentally fundamental bulk effects as the fractal "Hofstadter butterfly" spectrum, predicted several decades ago [4], but yet experimentally unobserved.

2. Spin-orbit coupling with an ultranarrow clock transition.

Ytterbium atoms are characterized by an electronic degree of freedom: in particular, they are characterized by a metastable state e=$^3P_0$ (lifetime about 23 s) that can be connected to the ground state g=$^1S_0$ by an ultranarrow "clock" transition.

- Investigation of fermionic superfluids with atoms in two electronic states. The interaction strength between atoms in the g and e states can be changed by using a recently-discovered "orbital Feshbach resonance" [4]. I propose to perform experiments aimed at the realization and characterization of fermionic superfluids, e.g. by transport properties to directly probe the superfluid character of the system and to determine the binding energies of the molecular states.

References

[1] M. Mancini et al., Science 349, 1510 (2015).

[2] L. F. Livi et al., Physical Review Letters 117, 220401 (2016).

[3] S. Barbarino et al., Nature Communications 6, 8134 (2015).

[4] D. R. Hofstadter, Physical Review B 14, 2239-2249 (1976).

[5] G. Pagano et al., Physical Review Letters 115, 265301 (2015).