Master in Photonics – "PHOTONICS BCN"
Master ERASMUS+ "EuroPhotonics"

MASTER THESIS PROPOSAL

Dates: April 2021 - September 2021

Laboratory: Ultracold Quantum Gases group
Institution: ICFO – The Institute of Photonic Sciences
City, Country: Castelldefels (Barcelona), Spain

Title of the master thesis: Novel imaging techniques for ultracold quantum gases

Name of the master thesis supervisor: Leticia Tarruell
Email address: leticia.tarruell@icfo.eu
Phone number: +34 935542254
Mail address: ICFO, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels (Barcelona)
Master thesis co-supervisor: Ramón Ramos, ramon.ramos@icfo.eu, +34 935542261

Keywords: ultracold atoms, quantum optics, atomic physics, Bose-Einstein condensates, high-resolution imaging

Summary of the subject:

In recent years ultra-cold atomic gases have emerged as a novel platform for the study of quantum many-body systems. Exploiting these gases, it is possible to synthesize quantum matter of highly controllable properties (interactions, dimensionality, potential landscape, etc.) in table-top experiments. In our group, we use them to explore experimentally collective phenomena originally studied in condensed-matter physics, such as superfluidity, supersolidity or magnetism.

Our group has currently a fully operational quantum gas apparatus. We have recently focused on the study of mixtures of Bose-Einstein condensates with laser-engineered spin-orbit coupling, which provides a link between the momentum and the spin of the atoms. At high coupling, this method simulates synthetic electric and magnetic fields for neutral atoms [1]. In particular, we have recently implemented a modification of this scheme where interatomic interactions become chiral, resulting in a density-dependent gauge field. This allows us to realize in our experiment an interacting gauge theory analogous to those describing the edges of fractional quantum Hall states.

We are currently pursuing the study of this system at low spin-orbit coupling strength. In this regime, the ground state of the system is in a superposition of spatially overlapping momentum states with equal amplitude but opposite sign [2]. This situation leads to a modulation of the density profile due to the interference of the two momentum components. The resulting state is a new exotic phase of matter, the supersolid, predicted almost 70 years ago [3] and that exhibits simultaneously the phase coherence of a superfluid and the crystalline structure of a solid.

The goal of this Master thesis will be to explore methods to improve the optical resolution of our imaging system to observe and characterize this novel state of matter. The project will explore the implementation of superresolution techniques (adapting techniques originally used to image biological samples to the quantum gas context [4,5]), the interferometric characterization and optimization of the optical system, and/or the improvement of our current imaging system through adaptive optics techniques.

For further information, references and a list of former Bachelor and Master projects completed in the group, please consult **www.qge.icfo.es**

[1] Y.-J. Lin, K. Jiménez-García, & I. B. Spielman, "Spin-orbit-coupled Bose-Einstein condensates", Nature 471 83 (2011).
[2] Y. Li, L. P. Pitaevskii, & S. Stringari, "Quantum tricriticality and phase transitions in spin-orbit coupled Bose-Einstein condensates", Phys. Rev. Lett. 108 225301 (2012).
[3] M. Boninsegni, & N. V. Prokof'Ev, "Colloquium: Supersolids: What and where are they?", Rev. of Mod. Phys. 84 759 (2012).
[4] M. McDonald, J. Trisnadi, K. X. Yao, & C. Chin, "Superresolution Microscopy of Cold Atoms in an Optical Lattice", Phys. Rev. X 9 021001(2019).
[5] J. P. Brantut, J. F. Clément, M. R. De Saint Vincent, G. Varoquaux, R. A. Nyman, A. Aspect, T. Bourdel, & P. Bouyer, "Light-shift tomography in an optical-dipole trap for neutral atoms", Phys. Rev. A 78 031401(R) (2008).

Additional information:

* Required skills: The candidate should have a good knowledge of optics and atomic physics, and a strong motivation to perform experimental work. Programming and previous experimental experience in optics are beneficial.

* Miscellaneous: The project will be carried out in a team of 4-5 people. The candidate will have his/her own project, but will participate in all group activities in order to maximize the learning experience.