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## **Master in Photonics – “PHOTONICS BCN” Master ERASMUS Mundus “EuroPhotonics”**

### **MASTER THESIS PROPOSAL**

**Dates: April 2021 - September 2022**

**Laboratory: Ultracold Quantum Gases**  
**Institution: ICFO**  
**City, Country: Castelldefels (Barcelona), Spain**

**Title of the master thesis: Experimental quantum simulation with ultracold quantum gases of potassium and strontium**

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**Keywords:** ultracold quantum gases, quantum simulation, Bose-Einstein condensates, degenerate Fermi gases, quantum liquids, gauge theories, supersolidity, optical lattices, quantum gas microscope, quantum magnetism.

#### **Summary of the subject (maximum 1 page):**

In recent years, ultra-cold atomic gases have emerged as a novel platform for the study of quantum many-body systems. They provide quantum matter that can be controlled almost at will using the tools of optics and atomic physics, and allows one to engineer a very broad range of model Hamiltonians in a single table-top experiment. This bottom-up approach comes very close to Feynman’s idea of a “quantum simulator” - a special purpose quantum computer that can solve problems currently out of reach for classical machines – and, besides enabling the study of long-standing physics questions, also gives access to completely new forms of quantum matter. In our group, we have two quantum gas laboratories that focus on complementary aspects of quantum gas research.

In the potassium lab, we investigate mixtures of quantum gases where the competition of interactions with different origins reveals the subtle effects of quantum fluctuations and stabilizes new phases. For instance, we exploit mixtures of Bose-Einstein condensates (BECs) to create the most dilute liquids existing in Nature, and use them to understand better the role of quantum correlations in quantum many-body physics [1]. Using lasers that couple two internal states of the atoms, we also engineer collective many-body states which are described

by topological gauge theories originally proposed in the context of fractional quantum Hall physics, and investigate their chiral properties [2]. Finally, in ongoing experiments we are trying to create a supersolid liquid: a phase which exhibits simultaneously the phase coherence of a superfluid, the crystalline structure of a solid, and forms self-bound droplets like a liquid.

In the strontium lab, we aim at synthesizing the cleanest and purest “solids”. To this end, we will trap quantum degenerate fermionic atoms in optical lattices - artificial crystals of light created by interfering laser beams - and probe their properties by detecting every single atom and lattice site using fluorescence imaging. With such quantum gas microscope, we want to perform quantum simulations of the Fermi-Hubbard model [3], which is believed to hold the key of high-temperature superconductivity. Moreover, because strontium has 10 internal states, we can extend our studies to “electrons” of spin larger than 1/2, for which completely new types of quantum magnets are expected. The strontium apparatus is currently under development. Our experiment already produces laser-cooled fermionic atoms at microkelvin temperatures. Our plan is to produce the first Spanish degenerate Fermi gas this year, and develop the quantum gas microscope during 2022.

We offer Master theses on the two laboratories. They will focus on the development of an experimental subsection of the apparatus, and will include a small theoretical part focusing on its design, and a larger experimental part consisting on its construction and characterization. Several projects are possible depending on the skills and interests of the candidates, and on the advancement of the experiments. Envisioned projects this year are the development of: i) an aberration-correction imaging system, to manipulate and image potassium gases with a spatial resolution of  $\sim 1 \mu\text{m}$ ; ii) a new laser system for optically-coupling potassium BECs near the 405 nm transition, to create longer-lived supersolids; ii) an ultra-stable laser to manipulate strontium atoms using the “clock” transition at 698 nm, to investigate a new scheme for spin-resolved quantum gas microscopy. For further information, references and a list of former Bachelor and Master projects completed in the group, please consult [www.qge.icfo.es](http://www.qge.icfo.es)

[1] C. R. Cabrera, L. Tanzi, J. Sanz, B. Naylor, P. Thomas, P. Cheiney, and L. Tarruell *Quantum liquid droplets in a mixture of Bose-Einstein condensates*, *Science* **359**, 301-304 (2018)

[2] A. Frölian, C. S. Chisholm, C. R. Cabrera, E. Neri, R. Ramos, A. Celi, and L. Tarruell, *Realizing a one-dimensional topological field theory in an optically-coupled Bose-Einstein condensate*, in preparation

[3] L. Tarruell and L. Sanchez-Palencia, *Quantum simulation of the Hubbard model with ultracold fermions in optical lattices*, *C. R. Physique* **19**, 365–393 (2018).

#### **Additional information (if needed):**

We are looking for candidates with a good background in quantum optics, atomic physics or condensed-matter physics, and a strong motivation for setting up and conducting challenging experiments in a team of three to four people. We offer training in a broad range of cutting-edge experimental techniques (from optics, electronics, ultra-high vacuum technology and computer control to quantum state engineering), as well as in theoretical atomic, quantum, statistical, and condensed matter physics.