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

MASTER THESIS PROPOSAL

Dates: April 2023 – July or September 2023

Laboratory: Atomic Quantum Optics (Mitchell group)
Institution: ICFO
City, Country: Barcelona, Spain

Title of the master thesis: Single-domain Bose-Einstein Condensate

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Keywords: Quantum sensing, atomic physics, quantum optics

Summary of the subject (maximum 1 page):

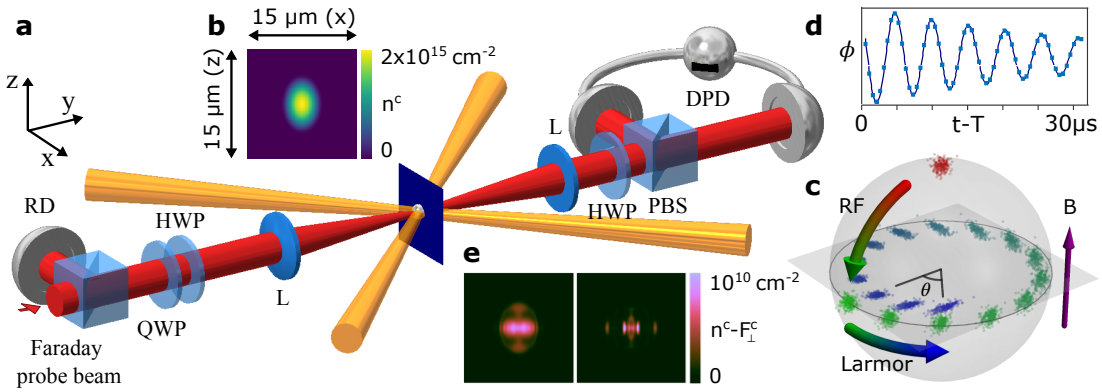

*Figure 1 Single-domain spinor BEC (SDSBEC) magnetometer schematic and principle of operation, from [1]. **a)** illustrates the experimental methods: a cold ^{87}Rb sample of ~70,000 atoms is loaded into a crossed optical dipole trap (yellow/orange beams) and evaporative cooling is used to produce a single-domain condensate. An off-resonance probe beam (red, Faraday probe beam) is passed through the condensate and experiences polarization rotation by an angle ϕ, proportional to the SDSBEC magnetization along direction y, is detected with polarization optics and low-noise differential photodetection. **b)** shows the atomic density, in the x-z plane. **e)** shows the*

deviation from perfect polarization, which is at the level of one spin, and thus in the worst case comparable to the spin projection noise. ***d)*** *shows the measured rotation angle versus time, which reveals the precession dynamics of the spinor condensate.* ***c)*** *shows the spin distribution evolution during a magnetometry sequence, in which the spins are first prepared along the magnetic field, tipped by a radio-frequency (RF) pulse into the x-y plane, experience: Larmor precession by and angle θ, relaxation due to loss of atoms, and shearing of the noise distribution due to competition of ferromagnetic and quadratic Zeeman effects. The resulting sensitivity is about two orders of magnitude beyond the sensitivity of any comparably-sized magnetic sensor [2].*

A spinor Bose-Einstein condensate is ultracold bosonic matter, in this case ^{87}Rb, cooled to quantum degeneracy and held in a state-independent trap (in practice, this means an optical trap, in which laser fields create a potential for the atoms that is the same for any of the atoms' low-lying internal states). We operate a spinor Bose-Einstein condensate in the single-domain regime, meaning that all of the atoms in the trap have the same state. In this regime, the atoms act as a single atom, and moreover have in practice no significant decoherence mechanisms – we see spin precession that lasts for ~8 seconds, which is the lifetime of atoms in the trap. This small (about 10 microns) BEC recently set a record for the highest size-normalized magnetic sensitivity of any sensor yet made [1]. We are are currently studying whether it can also be the most accurate thermometer, measuring temperatures into the picokelvin regime [3]. We even have some ideas to use this to detect the short-range forces that would be produced by dark matter [4].

[1] S. P. Alvarez *et al.*, PNAS **119**, (2022).
[2] M. W. Mitchell and S. Palacios Alvarez, Rev. Mod. Phys. **92**, 021001 (2020).
[3] E. Aybar *et al.*, Quantum **6**, 808 (2022).
[4] P. Gomez *et al.*, Phys. Rev. Lett. **124**, 170401 (2020).

Objectives:

As in any laboratory, there are many things to be done. We have ideas for projects ranging from A) stabilization of an optical resonator around the atoms, to enable quantum non-demolition measurement of the atomic spins, to B) design of a 2D magneto-optical trap to enable faster loading of the trap and better vacuum conditions, to C) calculation of quantum noise dynamics in the BEC as it searches for new forces. Please come to talk with us so we can see if your skills and interests match our project needs.

Additional information (if needed):
* Required skills: Experimental experience is desirable but not absolutely required. Hard working, good knowledge of optics and laser physics, knowledge of atomic physics.
* Miscellaneous: Project will be done at ICFO.