Quantum entanglement & metrology with inertial sensors

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Context:

The field of atom interferometry has rapidly developed since the last 30 years and enable precision measurements by mapping the physical quantity of interest to a phase shift determined using interferometric techniques [1]. Free-fall atom interferometers are extraordinarily sensitive to external forces and find key applications as gravimeters, gradiometers, and gyroscopes in applied physics and fundamental science [2]. State-of-the-art devices use N uncorrelated atoms and their phase estimation uncertainty is lower bounded by the standard quantum limit (SQL): $\Delta\phi_{SQL} = 1/\sqrt{N}$. Since N is generally constrained by the experimental apparatus or by the onset of unwanted systematic effects due to the high density, the possibility to overcome the SQL by engineering specific quantum correlations [3] between the atoms is attracting increasing interest. A major breakthrough in the field of Quantum Metrology relies in the use of entangled states to fully exploit quantum advantages and ultimately reach the Heisenberg limit: $\Delta\phi_H = 1/N$.

Quantum-enhanced atom interferometry has mainly focused on atomic clocks and magnetometers and so far, free-fall atom interferometers have received less attention. These measurement devices have stringent practical requirements. The generation of atomic entanglement must be compatible with the splitting of the atomic wave packets in well-defined and well-controlled external momentum modes with high efficiencies.

Project:

The internship will be carried out in close collaboration with an experimental team and will focus on the theoretical and numerical study of spin-squeezing dynamics in Bose–Einstein condensates [5]. The main objective is to investigate how entanglement can improve the phase sensitivity of quantum inertial sensors while keeping their accuracy when accounting for different experimental defects. The intern will develop analytical models and perform numerical simulations to study spin squeezing in different experimental configurations, including trapped [6], free-falling [7], and differential atom-interferometer setups [8]. The project will provide the opportunity to work at the interface between quantum optics, ultra-cold atoms, and quantum sensing, with direct interaction between theoretical and experimental activities.

This offer is dedicated for M1, M2 and Engineer gap year student looking for a 5 to 6 month internship.

Prerequisites:

Quantum-optics, Quantum mechanics, knowledge in C, Fortran90, Python or Matlab, a pronounced taste for numerical and analytical calculations.

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[4] S. S. Szigeti et al., High-precision quantum-enhanced gravimetry with a Bose-Einstein condensate, Phys. Rev. Lett. **125**, 100402 (2020).
[5] M. Kitagawa and M. Ueda, Squeezed spin states, Phys. Rev. A **47**, 5138 (1993).
[6] R. Corgier et al., Phys. Rev. A, **103**, L061301 (2021).
[7] R. Corgier et al., Delta-kick Squeezing, Phys. Rev. Lett. **127**, 183401 (2021).
[8] R. Corgier et al., Optimized squeezing for accurate differential sensing under large phase noise, Quantum Sci. Technol. **10** 045016, (2025)