M2 Thesis project – Laboratoire Système de Référence Temps Espace (SYRTE)

Quantum enhanced metrology with inertial sensors

Team: Interférométrie Atomique et Capteurs Inertiels (IACI)
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Context of the research work:

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 [2] are extraordinarily sensitive to external forces and find key applications as gravimeters, gradiometers, and gyroscopes in applied physics and fundamental science [3]. State-of-the-art devices use N uncorrelated atoms and their phase estimation uncertainty is lower bounded by the standard quantum limit (SQL): $\Delta\phi_{SQL} = 1/\sqrt{N}$, where N is the number of atoms. 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 [5] between the atoms is attracting increasing interest [6]. 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 [7] and magnetometers [8] and so far, free-fall atom interferometers have received less attention [9]. 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. Very recently, Bose-Einstein condensates (BECs) have been pinpointed as ideal candidates [10, 11] and a scheme based on the "Delta-kick Squeezing" method, illustrated in Figure 1, has been proposed [12].

M2-project:

The project aimed to be developed in close interaction with the experimental team with the development of analytical and numerical simulations to study the creation of spin-squeezing dynamic [13]. The first objective consist on the study of the dynamic of Bose-Einstein condensate based on analytical and full-numerical simulations. The goal is to highlight different experimental configurations leading to spin-squeezing dynamics [13]. The second objective consist on an analytical study of presence or not of spin-squeezing dynamic in the output port of the interferometer when experimental imperfections are present.

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

Extension & PhD-project:

You have a taste for theoretical work at the interface with real experiments at the state of the art in the field and you would like to take them further with theoretical protocols ?

The PhD candidate will contribute to a breakthrough in the field of Quantum-Enhanced Metrology measurement with atom-interferometer with a full simulation of the “Delta-kick Squeezing” protocol currently under investigation in a real quantum-gravimeter developed at SYRTE.

The candidate will benefit from pre-existing results from the team in the field, as well as long-standing collaborations with external theoretical and experimental partners. The candidate will interact with different experimental team to test her/his protocols on state-of-the-art devices.

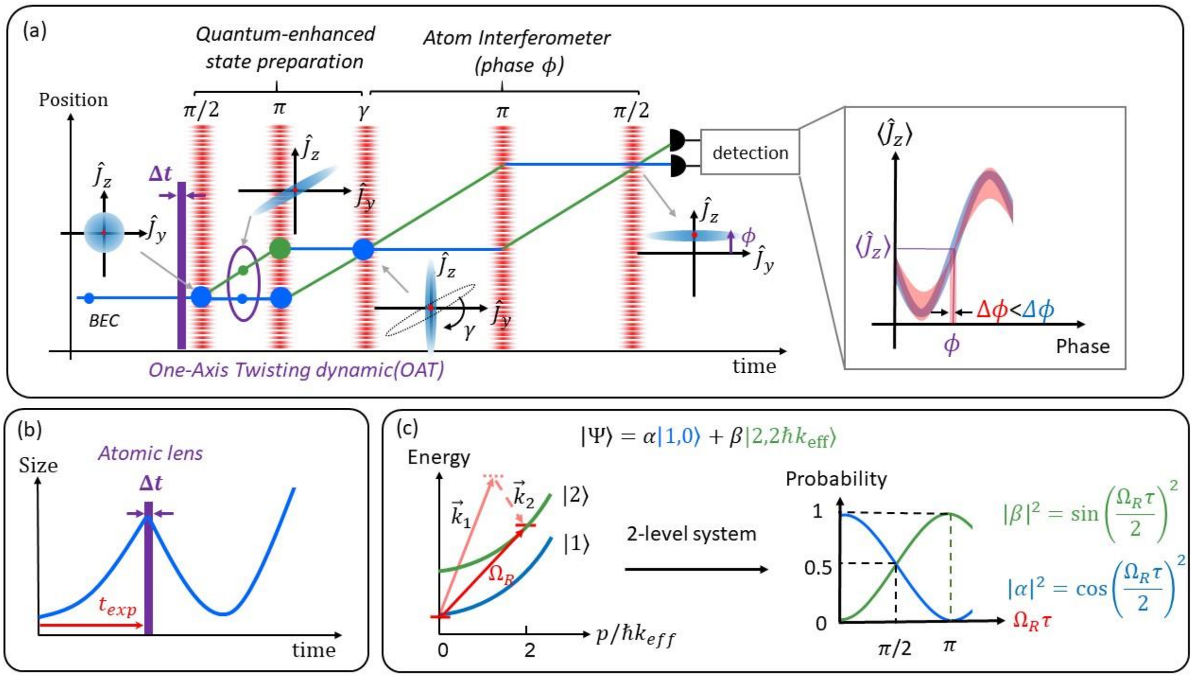

Figure 1 : Concept of the Delta-kick Squeezing and atom-interferometry measurement. Panel a: A preliminary quantum-state preparation enables the creation of spin-squeezed state by the combination of an atomic lens (b) and three atom-light pulses (c) reproducing optical beam-splitter and mirror elements. The generated quantum state is used in a Mach-Zehnder atom-like interferometer. The phase accumulated is evaluated by counting the number of atoms at the output port (detection). The quantum-state evolution is shown in light blue within a quantum-optic representation where $\hat{J}_y \equiv \hat{x}$ and $\hat{J}_z \equiv \hat{p}$. The initial input state is an interacting BEC. After dilution and before the first $\pi/2$-pulse generating a coherent spin-state (blue disk) an atomic lens consisting in flashing for a short duration an harmonic trap is applied to focus the BEC at a later point (b). The atom-atom interaction plays the role of a Kerr non-linear medium and deforms the quadrature of the quantum state through the One-Axis-Twisting dynamic (OAT) [13]. Panel b: Principal of the atom lens to focus the BEC at a given time in analogy to optics. Panel c: Principal of the two-photon transition to imprint a momentum kick to one part of the quantum state generating the separation of the two partial-waves in analogy to optics. The quantum state can be described by a 2-level system and the quantum superposition can be controlled through the interaction between the atoms and the light for a duration τ with the effective Rabi frequency Ω_R.

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