Title : Theoretical study of quantum gas experiments in an Earth-orbiting research laboratory

Keywords : Bose-Einstein condensate, quantum-degenerate mixtures, microgravity

One of the major goals of fundamental physics is to unify general relativity, which describes macroscopic phenomena driven by the influence of gravity, with quantum mechanics, which focuses on effects at microscopic scales. Ensembles of cold atoms, as massive quantum objects, lie at the crossroads of both theories and appear as a test object of choice. They can be used to test theories that postulate a violation of Einstein's Equivalence Principles, in particular a violation of the Universality of Free Fall (UFF).

Recent proposals suggest using mixtures of Bose-Einstein condensates (BEC) as sources for precision atom interferometry to perform UFF. These have the potential to match the precision of the best tests with classical test masses performed during the MICROSCOPE mission, and may even provide better results in the long term. The realization of experiments in microgravity, where atoms can float for long periods of time, allows longer interrogation times, thus increasing the performance of matter-wave sensors. To optimize the implementation of UFF tests, one needs exquisite control of the atoms due to stringent requirements on the error budget. In this work, we focus on the design of the input state with control over the position and velocity of the atom clouds, as well as their size evolution.

The experiments studied here are designed with atom chip setups that manipulate atoms with magnetic traps. Most of the applications presented are experiments performed in the NASA Cold Atom Laboratory (CAL) aboard the International Space Station as part of the Consortium for Ultracold Atoms in Space (CUAS). This multi-user BEC machine allows the manipulation of single species BEC at its installation as well as dual species mixtures after upgrades. Following this chronology, we first study the dynamics of single species BEC and then extend the work to the manipulation of an interacting mixture of two BECs. The first step after calibrating the chip model is to design a fast and robust transport protocol to move the atoms away from the atom chip. We present and use a Shortcut-To-Adiabaticity (STA) protocol, based on reverse engineering, to transport the BEC and meet the requirements of position control at the sub-µm level and velocity control at the hundreds µm/s level. The free expansion of the atom cloud with its inherent atomic density drop makes signal detection difficult. By analogy with light, it is possible to collimate the atom cloud with atomic lenses using the Delta-Kick Collimation (DKC) technique. Application to CAL resulted in expansion energies in the tens of pK level. To simulate the imaging process and to support the data analysis, theoretical models, that take into account the resolution effects of the camera and the frame transformations associated with the orientation of the camera or the orientation of the trapping potential with respect to the atom chip, are presented

Space allows the operation of Bose-Einstein condensate mixtures under miscibility conditions not possible on the ground. The colocation of the trap center for the different species in microgravity can lead to different topologies of the trap ground state. Moreover, the interaction energy between the species, which is almost negligible in the ground state, plays a significant role in the dynamics of the mixture during its transport. However, the simulation of the dynamics of interacting dual-species BEC mixtures is computationally challenging, particularly due to the long expansion times. In this work, scaling techniques to overcome these limitations are presented and illustrated in the case of space experiments in CAL and aboard sounding rockets. Such scaled-grid approaches make it possible to simulate long transports with free expansion times on the order of seconds, which would not be feasible with a fixed-grid approach on reasonable time scales, not to mention the problems of memory usage.