Centre for Quantum Materials and Technology

Ph.D. Project 2022-2025

Quantum Control of Gravity with Levitated Mechanical Systems

Project supervisors: **Mauro Paternostro** & **Matteo Carlesso**
Contacts: **m.paternostro@qub.ac.uk**

State of the art and motivations

The investigation on the potential quantum mechanical nature of gravity is one of the key questions in the panorama of modern physics. While recent developments that highlighted that potentially significant advantages stem from the use of an information theoretic approach to such problem, the development of quantum technologies poses a fantastic opportunity to deploy techniques of quantum sensing and metrology to the task. This is precisely the context where this project will be developed.

The main objective is to demonstrate the proof of concept of a levitated acceleration sensor and its ability detecting gravity of small masses and in the quantum controlled regime. We will explore the interplay between quantum mechanics and gravity in a parameter range accessible for cost-effective table-top experiments. We will consider suspended sub-millimetre particles in optical and magnetic traps and use those to detect gravitational forces in an unprecedented mass regime, thus addressing some of the most fundamental theoretical questions through an original approach. The project will be developed within the context of a theory-experiment collaboration involving experimentalists in Southamptoon and The Netherland, and theorists in Germany and Italy with which a strong interaction is anticipated.

Objectives & Methodology

The overarching goal of this project is to design schemes for the ultra-precise sensing and metrology of extremely weak forces through levitated opto- and magneto-mechanical devices. By focusing on the centre-of-mass and rotational degrees of freedom of optically or magnetically levitated particles, we will access the so far unexplored regime where gravity and quantum mechanics coexist and affect the dynamics of a physical system. We will address such needs to achieve the following main goals:

(i) Quantum control of levitated opto/magneto-mechanics. The crucial line of research is to understand how quantum states of matter can be prepared with the help of light and magnetic manipulation. Our research goal is to expand the quantum control capabilities of quantum systems, such as to generate entanglement or superposition, to opto/magneto mechanical systems in the mass range of 10^{-18}kg to 10^{-12}kg.

(ii) Measurement based quantum control of opto/magneto-mechanical systems. We will use optical measurements to prepare quantum states as a technique for quantum state preparation, especially continuous weak interaction as in the levitated experiments at Southampton. We will utilize measurement based schemes to prepare quantum states of matter, employing parameter estimation, and sophisticated techniques such as real-time Kalman filtering and feedback.

(iii) Non-equilibrium non-linear dynamics in opto/magneto-mechanical systems. Light-matter interactions offer a large variety of interaction regimes that can be utilized for quantum control. We will study the non-equilibrium non-linear interactions in the mechanical system via hybridizations with other e.g. optical quantum systems. We will use intrinsic and induced non-linearities in translational and rotational motion of the mechanical system to prepare quantum states, such as superposition and entangled states and will use phase-space Wigner function analysis of the prepared states and the assessment of the features of the dynamics making use of tools of phase space-based non-equilibrium thermodynamics.

Collaborations

As mentioned, the work entailed by this project will be performed within the context of a collaborative network involving the University of Southampton, the University of Trieste, Universität Tübingen and the Leiden Institue of Physics.

The project will benefit from in-house interactions with members of the Quantum Technology Group, specifically S. Donadi, A. Belenchia, Alessandro Ferraro, and Gabriele De Chiara.

Required skills

The candidate student will have excellent mathematical and physical background. A good knowledge of Quantum Theory will be required while knowledge of elements of Quantum Information Processing will be desired. A natural inquisitive and curious mind associated with originality and creativity in the approach to problems will be appreciated. Advanced computing skills are not required, although the student will become familiar with instruments such as Python and Mathematica.

Further information

For further information contact Prof. Paternostro: **m.paternostro@qub.ac.uk**