Quantum Control of Gravity
with Levitated Mechanics

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Group picture at the Doctoral School Fundamental Problems in Quantum Physics 2023
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Summary

Update of work done

We have been developing a feedback-based scheme for controlling the motion of levitated particles, as well as coupling a continuous variable harmonic oscillator to a discrete variable quantum system for control purposes. The scheme is for cooling and/or squeezing the motion based on a position measurement with the detection efficiency being the key parameter for optimisation in experiments. We have applied such a scheme to optical levitation experiments and have achieved cooling and squeezing, as well as a vibration based linear cooling scheme for magnetic levitation. The position measurement in the optical trap has been optimised by using a parabolic mirror re-collimating the backwards scattered light, which is known to carry the majority of information about the z-motion of the trapped particle, for efficient detection. In the superconducting Meissner traps detection is done by SQUIDs and the detection efficiency has been optimised by the coupling pick-up antenna geometry and distance to the trapped particle. A major next step will be the use of dedicated superconducting circuit designs for detection and control. Both experiments are ongoing during the next reporting period of QuCoM, and will be reported as per relevant WP deliverables.

We have been working intensely on exploring the effects of control of non-linearities on the motional states of trapped particles. The goal is to generate non-Gaussian states towards quantum state preparation and this non-linear scheme is regarded as a promising pathway to achieve such states, including spatial quantum superposition states. The approach is to access intrinsic Duffing-type non-linearities of the trapping potentials by enhancing the amplitude of oscillations a squeezing operation. The control is arranged on a pulsed operation by fast changing the trap’s spring constant in tune with the oscillation period while additional parametric feedback cooling can be used in addition to keep the particle inside the trap. The squeezing&cooling&non-linear scheme is explored for both optical and magnetic traps and preliminary experimental results have been achieved, based on theory.

As a first, preliminary step towards the construction of a framework for the precision measurement of gravity, Tübingen and QUB made use of the powerful formalism of quantum parameter estimation to assess the characteristic rates of a Continuous Spontaneous Localisation (CSL) model affecting the motion of a massive mechanical system. This embodied/was intended to be used as an easier benchmark case-study to consider before addressing the full-fledged gravitational case o.

By considering the non-equilibrium conditions of an intra-cavity levitated optomechanical system, the QuCoM team has investigated the advantages provided by the combined use of quantum correlated input-noises and EPR-like measurements in the estimation of the CSL parameter. When short evolution times are considered, such a quantum approach turns out to be better than a classical strategy. However, the advantage is lost at the steady-state, where a classical measurement scheme and an uncorrelated vacuum input-noise outperform EPR-like measurement and quantum correlated two-mode squeezed input-noises. We believe this is valuable information for any experimental effort aimed at pinpointing the potential occurrence of collapse-like mechanisms on the dynamics of a quantum system. In particular, it highlights the benefits that a non-equilibrium regime provides in magnifying the advantages provided by quantum resources.

We have analyzed three gravity-related quantum models: i) The Schrödinger-Newton equation, which predicts that different parts of the quantum wave function attract gravitationally; ii) Károlyházi's model, according to which classical spacetime fluctuations limit the quantum properties of physical systems, and iii) The Diosi-Penrose model, which predicts that gravity causes the collapse of the quantum wave function.

As for the Schrödinger-Newton (SN) equation, we studied the effect of a quadrupole term $F_0\cos(\Omega t)$ in the dynamics of the center-of-mass motion subject to a harmonic potential of frequency ω_{CM}. We considered a mass of M=1.67x10^{-12} kg, frequency ω_{CM} = 2π x 0.1 s^{-1}, and Schrödinger-Newton frequency ω_{SN}=0.036 s^{-1}, and we saw that by setting F_0=2.02 x 10^{-12} kg/s^2 and Ω=2.607 s^{-1}, we observe an amplification of the position variance of the system. Regarding Károlyházi's model, the original proposal was ruled out by comparison with experimental observations, but we considered a natural generalization that restores compatibility with experimental data. For a factorized correlation function, we show that the allowed range of values for the spatial parameter R_k, considering data from X-ray experiments with photons having frequencies $\omega = 10^{20}\ Hz$, is $0.11\ m \leq R_k \leq 1.98\ m$. Regarding the Diósi – Penrose model, we are currently working on setting an upper bound on the free parameter R_0 of the model. Preliminary analyses suggest that we might be able to rule out the model by setting an upper bound of the order of 10^{-9} Å, which is about nine orders of magnitude smaller than the lower bound available experimentally, which is of the order of 1 Å.

The assessment of the phenomenology of gravity on a quantum system would pass through a careful assessment of the decoherence mechanism induced by a gravitational mechanism. The original standing point of QuCoM in this regard is built around the realisation that an explicitly non-equilibrium approach would be very beneficial. To benchmark it, we have addressed a preliminary problem aimed at studying the phenomenology leading to the non-conservation of energy of the CLSL model from the viewpoint of non-equilibrium thermodynamics, and use such framework to assess the equilibration process entailed by its dissipative formulation (dCSL). The experimental setting at the core of QuCoM -- i.e. a mechanical system undergoing controlled dynamics -- served a paradigmatic case study. We have performed our analysis in the phase space of the oscillator, where the entropy production rate, can be conveniently analyzed. We have shown that the CSL model violates Clausius law, as it exhibits a negative entropy production rate, while the dCSL model reaches equilibrium consistently only under certain dynamical conditions, thus allowing us to identify the values -- in the parameter space -- where the latter mechanism can be faithfully used to describe a thermodynamically consistent phenomenon. The next step in our investigation will be the application of such tools of an exquisite thermodynamic nature to the assessment of gravity-induced decoherence mechanisms.

Publications

The following list includes publications of the last 6 months (April – September 2023):

Authors	Title	Journal	Volume	Pages	Year
Domenico Ribezzo et al.	Deploying an Inter-European Quantum Network	Advanced Quantum Technologies	6	2200061	2022
Kristian Piscicchia et al.	A Novel Approach to Parameter Determination of the Continuous Spontaneous Localization Collapse Model	Entropy	25	295	2023
Fabrizio Napolitano et al	Underground Tests of Quantum Mechanics by the VIP Collaboration at Gran Sasso	Symmetry	15	480	2023
Angelo Bassi, Mauro Dorato and Hendrik Ulbricht	Collapse Models: A Theoretical, Experimental and Philosophical Review	Entropy	25	645	2023
Sandro Donadi, Luca Ferialdi and Angelo Bassi	Collapse Dynamics Are Diffuse	Physical Review Letters	130	230202	2023

Anirudh Gundhi and Angelo Bassi	Motion of an electron through vacuum fluctuations	Physical Review A	107	062801	2023
S. Hernández-Gómez, S. Gherardini, A. Belenchia, A. Trombettoni, M. Paternostro and N. Fabbri	Experimental signature of initial quantum coherence on entropy production	npj Quantum Information	9	86	2023
Giovanni Di Bartolomeo, Matteo Carlesso, Kristian Piscicchia, Catalina Curceanu, Maaneli Derakhshani and Lajos Diósi	Linear-friction many-body equation for dissipative spontaneous wave-function collapse	Physical Review A	108	012202	2023
L. Innocenti, S. Lorenzo, I. Palmisano, A. Ferraro, M. Paternostro, and G. M. Palma	Potential and limitations of quantum extreme learning machines	Communication Physics	6	118	2023
Ilaria Gianani, Alessio Belenchia, Stefano Gherardini, Vincenzo Berardi, Marco Barbieri, and Mauro Paternostro	Diagnostics of quantum-gate coherences deteriorated by unitary errors via end-point-measurement statistics	Quantum Science and Technology	8	045018	2023
Gabriele Lo Monaco, Luca Innocenti, Dario Cilluffo, Dario A Chisholm, Salvatore Lorenzo and G Massimo Palma	Quantum scrambling via accessible tripartite information	Quantum Science and Technology	8	035006	2023
D.A. Chisholm, L. Innocenti, G.M. Palma	The meaning of redundancy and consensus in quantum objectivity	Quantum	7	1074	2023

Dissemination activities

In the last 12 months, QuCoM members delivered a total of 51 seminars and talks.

Moreover, in the frame of QuCoM activities, the following workshop and seminars were organized:

1. **Optomechanical systems for tests of fundamental physics** – 5/12/2022

In light of the kicking off of the QuCoM activities in Trieste, Dr. Matteo Carlesso has been invited to deliver a series of seminars on optomechanics applied to fundamental tests of Quantum Mechanics to the Trieste group. Part of the tasks of the group are to devise novel experimental schemes for exploring the quantum-gravity interplay and for testing alternative models which try to combine the two theories. Optomechanics, at the core of QuCoM, is among the most promising platforms for such tests.

2. **QuCoM scientific workshop** - 22/06/2023 – 23/06/2023

PIs and team member of the QuCoM project, 17 participants in total, have met in person for a 2-day scientific meeting to update on progress and to define next steps and new collaborations to achieve the objectives of the QuCoM project. The Steering Committee has also met to discuss preparation for the end of the reporting period. Moreover, the host Leiden University organized a lab tour for the participants who had opportunity to have informal discussions in small groups. Experimentalist had a structured meeting for internal updates.

3. **COLMO: Quantum Collapse Models investigated with particle, nuclear, atomic and macro systems** - 3/7/2023 – 7/7/2023

The COLMO (Quantum Collapse Models investigated with Particle, Nuclear, Atomic and Macro systems) workshop aims to advance the understanding of Quantum Collapse, by bringing together theoreticians and experimentalists working in the field. New realistic dissipative and non-Markovian collapse models are being developed, including gravity-related ones, to solve a major conundrum in quantum physics: identification of a physical mechanism for the collapse of the wave function. At the same time, experimentalists search for signatures of the proposed collapse models with various and very different physical systems. Searches of anomalous heating, or of spontaneous radiation are performed in atomic, nuclear, and mesoscopic/macroscopic systems from underground laboratories to (planned) space-based experiments. A collaborative discussion of the various experimental approaches towards an optimized search of collapse model signatures is timely. COLMO will bring together the communities working in quantum collapse with the aim to set up a synergetic effort towards progress in the field. All the information about the conference can be found at https://www.ectstar.eu/workshops/colmo-quantum-collapse-models-investigated-with-particle-nuclear-atomic-and-macro-systems/

4. **A look at the interface between gravity and quantum theory** - 11/7/2023 – 13/7/2023

The workshop will gather young researchers working in topics at the interface between gravity and quantum mechanics. PhD students and PostDocs will be given the opportunity to present their research activity and interact with their colleagues, share motivations, techniques and perspectives, in a friendly and informal environment. A great amount of time will be dedicated to discussions and perspectives. The workshop is limited to a small number of attendee. If you are interested to attend, please consider registering as soon as possible. If your schedule changes and you are not able to attend after having registered, please let us know as soon as possible. All the information about the conference can be found at qmts.it/?q=gravity-quantum/2023

5. **Quantum sensing and fundamental physics with levitated mechanical systems** - 31/7/2023 – 4/8/2023

The workshop Quantum sensing and fundamental physics with levitated mechanical systems aims at bringing together theorists and experimentalists working in the field of levitated nano/micromechanical systems, using various platforms (optical, electrical, magnetic) and in related fields in order to discuss the most recent results and exchange ideas in order to explore new opportunities in quantum sensing and fundamental physics. In particular, the workshop will cover the following topics: levitated optomechanics, levitated magnetomechanics, levitated micro and nanosensors, hybrid quantum systems, spin-mechanics, search for dark matter or modified gravity or new physics beyond the standard model, fundamental science in space. All the information about the conference can be found at https://www.ectstar.eu/workshops/quantum-sensing-and-fundamental-physics-with-levitated-mechanical-systems/

6. **Fundamental Problems in Quantum Physics 2023** – 13/9/2023 - 15/9/2023

Third school on quantum foundations dedicated to Prof. GianCarlo Ghirardi. Quantum Mechanics is extremely successful in predicting experimental results and has a vast range of applications. Nonetheless, many unanswered questions remain. The school will introduce Master and PhD students to the still outstanding problems in our understanding of quantum foundations.

To give a deep look into the foundations of quantum mechanics, lectures will be given by experts in the field. An extensive time will be dedicated to selected contributed talks. All the information about the conference can be found at http://www.qmts.it/?q=fpqp2023.