NEWSLETTER N.11, December 2020

300 mK plate construction of the He-3 insert of the cryostat at Southampton. Visible are SQUID detector above a lead trap at the bottom plate of the 300 mK assembly, as well as a geophone sensor for reference measurements of vibrational noise at the 1 K plate. Also visible are wire connectors all the way down to the 300 mK plate for the optional assembly of a Paul ion trap at the cryostat. *Credits: UoS*

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HIGHLIGHT: TEQ's second Review Report

Following TEQ's second Review Meeting on September 15, 2020 the Review Report came in and it makes us again very proud. "The contribution to the state of the art is significant, mainly to the field of levitated optomechanics, quantum sensing and quantum gravity. In general, TEQ contributes to fundamental physics and quantum technology. The scientific quality of the results from the project is very high" says the report. "The publication of project results in both theory and experiment in peer-reviewed, high quality research journals attests to their scientific quality", says the document about the TEQ publications. "The ongoing work is well aligned with the work plan", even though "there have been delays with experiments (especially WP3) due to COVID19. There is no impact on the 2nd period, but these delays expected to impact the 3rd reporting period.". Finally, the Commission states that "the project does scientifically very well and according to plan. There is no need for corrective actions.". We would like to thank the PO and monitors who have been very professional, involved and helpful throughout the process.

UPDATE OF WORK DONE

The **UNITS** activity mainly concerned the interplay between gravity and the quantum theory. The group analyzed the effects of environmental decoherence on experimental proposals for discerning whether gravity is fundamentally quantum or classical, and proposed a non-relativistic model for the gravitational decoherence of fermions coupled to an external classical electromagnetic field. The Trieste node compared different models describing gravity as fundamentally classical and mediated by a classical stochastic channel. It also investigated Penrose proposal of gravity induced wave function collapse, and showed that under fairly general assumptions the master equation describing Penrose proposal coincides with the one of the Diosi model. Furthermore, the group studied the effects of collapse models on scalar curvature perturbations and corresponding power spectrum during inflation and the radiation dominated era. It was found that the effects are largely negligible when compared to observations.

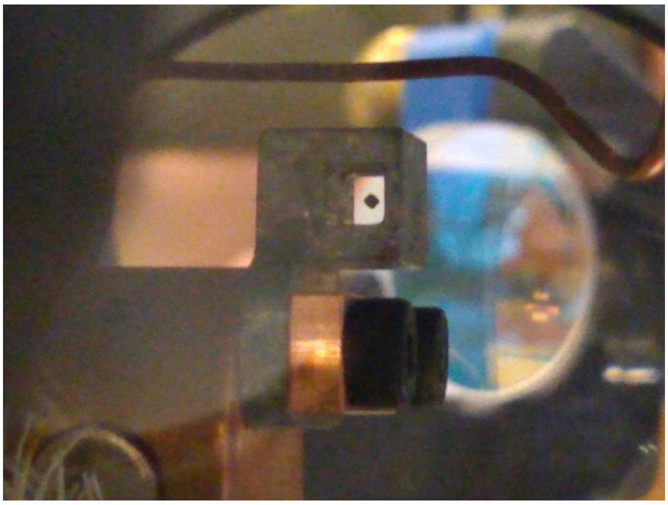
The activity of the **LNF-INFN** group was mostly dedicated to support and collaboration with UCL staff for the use of the low-noise electronics previously developed by LNF which, after characterization and qualification, was sent to UCL. In particular, the voltage amplifier AC/DC/Mixer which was realized after having decided the specifications in dedicated meetings and discussions with the UCL group was installed and started to be tested at UCL with support from LNF. The activity is undergoing based on online meetings and virtual (on LNF side) work with UCL colleagues, and is mostly focused at this stage on reducing the electronic noise on the overall setup revising the schematics and connections of various modules, including the grounding. The LNF team is planning to develop a new electronic version, function of the findings of the undergoing tests. The group is also developing tools for refined statistical analyses methods (Bayesian) of the data, by the new Post Doc Fabrizio Napolitano who started his activity in Spring 2020.

QUB has formalised an approach based on Quantum Hypothesis Testing (QHT) for the discrimination of competing hypotheses related to the presence of collapse effects in the dynamics

of a quantum system or lack thereof. The QHT framework was applied to an optomechanical system composed of two cavities, showing that squeezed optical input noise and feasible measurements on the output cavity modes, allow to obtain an advantage with respect to any comparable classical schemes. The research group has applied these results to the discrimination of models of spontaneous collapse of the wave function, highlighting the possibilities offered by this scheme for fundamental physics searches.
In collaboration with the University of Southampton, QUB has explored the perspective of near-field interferometry performed on large dielectric nano-particles for the testing of fundamental modification of standard quantum mechanics. They have showcased the capabilities of such platform, in a state-of-the-art ground-based experimental set-up, to set new stringent bounds on the parameters space of collapse models and highlighted the future perspective for this class of experiments.

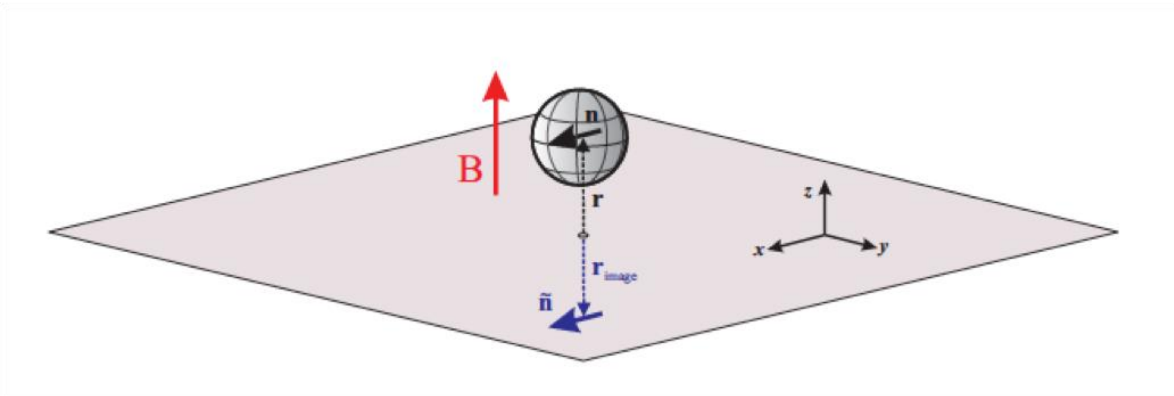
In the last six months, UCL group has heating in the Paul trap due to voltage noise and are currently modifying electronics to reduce this to reach the TEQ requirements. A detailed study of parametric and velocity feedback cooling has been carried out. The research group has also explored in detail the rotational motion of the Yb:YLF crystal fabricated by Delft. Finally, the noise in the laser supplied by M2Lasers, which was precluding Yb:YLF cooling and trapping experiments, has now been rectified. Due to this progress, researchers at UCL have recently started retesting the optical properties of newly grown Yb:YLF crystals from TUDelft.

At Southampton the team has restarted experimental work, still under COVID-19 restrictions and at limited capacity. It has continued to work on Meissner trapping ferromagnets at the size range of 10 micrometer in diameter. The team has optimised the geometry of the lead piece to isolate and separate the mechanical modes of the motion of the trapped particle. A further trap of parabolic trap shape has been built as well to allow for free rotation of the particle around one axis. This geometry may allow to generate precession motion at application of a tiny homogenous external magnetic field - in analogy to Lamor Spin physics.

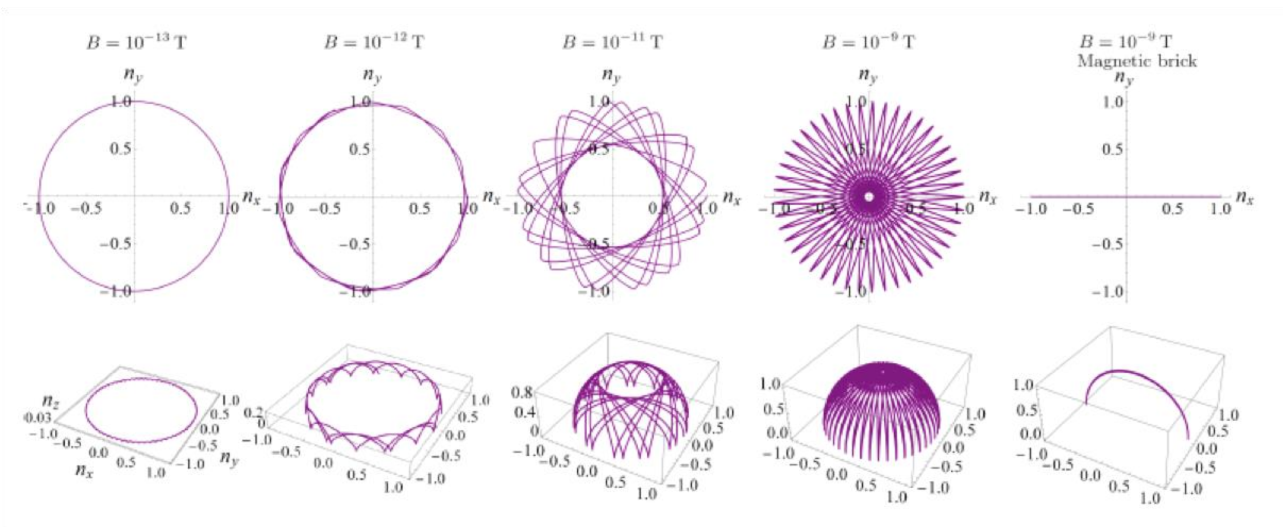


1. A levitated mm-sized ferromagnet in a 3-dimensional lead trap at a 4 K setup to test trap geometries for separating the different translational and rotational degrees of freedom in frequency. The advantage of this macroscopic trap with a comparably large particle is that the particle's motion can be easily optically detected with a camera. The study of this trap geometry has informed the shape on the new trap which will be used at 300 mK for the CSL test experiments. *Credits: UoS*

Initial tests of the new traps were performed in a 4 K setup and will be shifted on to experiments at 300 mK as well. Estimates are that for tests with a 10 micrometer diameter particle, the standard CSL model will be tested at a level of r-c=1e-5 m and \lambda=1e-13 Hz, which is already competitive with existing tests. The plan is to then reduce the size of the particle and increase its mechanical quality factor and signal to noise ration by reduction of vibrational noises. This will allow improving the testing of the standard CSL model. Depending on the achievements of this tests, we will decide in early 2021 if the Paul trap from UCL with the low-noise electronics from Frascati and Aarhus will go into the 300 mK cryostat at Southampton. A theory paper to use the precession motion of a trapped ferromagnet as a magnetic gyroscope to test fundamental physics has been submitted to a journal for publication. A further paper on using the ultra-narrow spectral features of a magnetic levitated particle in the range of 10 micro-Hertz have been used to set bounds on several theoretical models including the dissipative CSL and DP models.

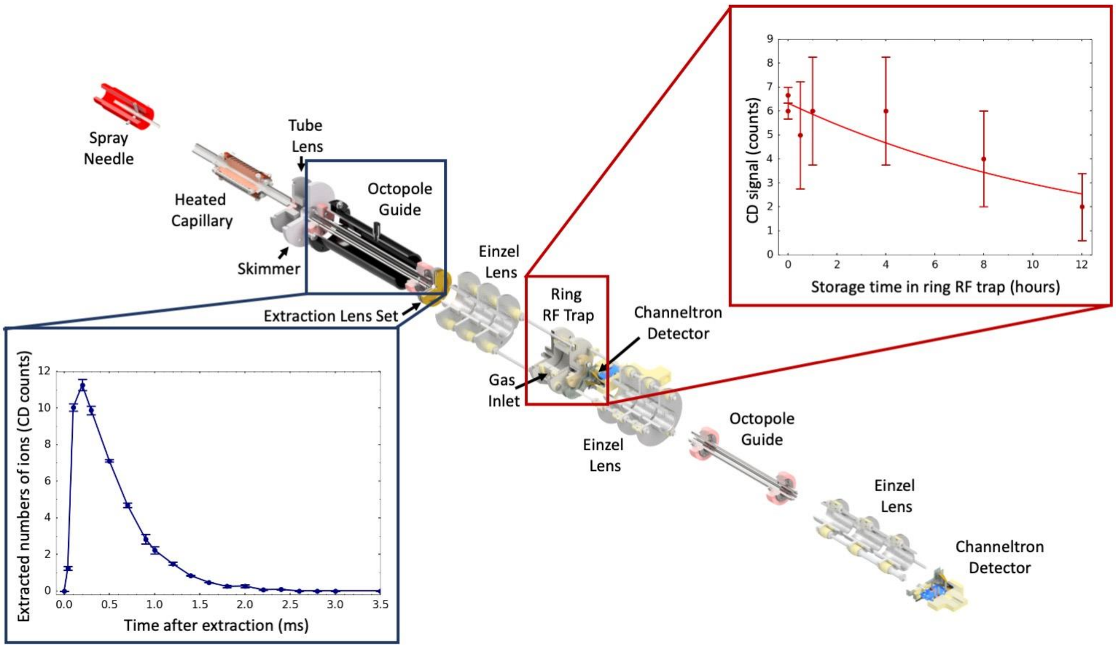


2. The schematics of the physics of the Meissner trap, where the particle's effective magnetic dipole is interacting with the image dipole generated in the lead trap. The particle's dipole ability to freely rotate around the z-axis upon the application of the external homogeneous magnetic field B is key to use the ferromagnet as a gyroscope. *Credits: UoS*



3. The trajectories of the gyro precession motion upon application of magnetic fields of different strength. Clearly visible are distinct motional features and a rich structure of spatial movements as part of this rotational motion, which may be used for sensing CSL noises amongst other effects. *Credits: UoS*

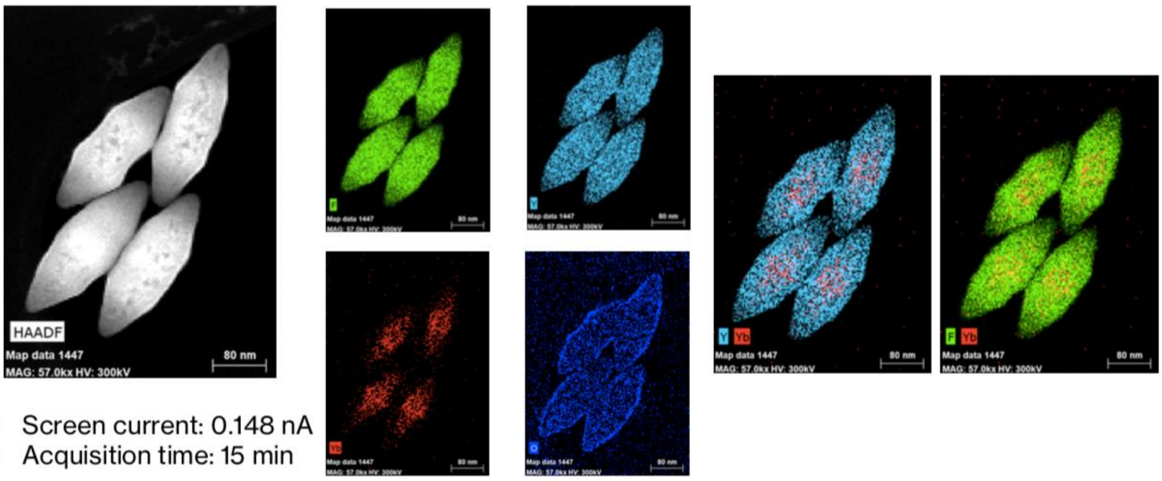
During the past few months the **AU** partner has made an electrospray source (ES) operational for the investigations into the prospect of using highly charged complex molecular ions as test objects for collapse models considered within TEQ (see Fig. 4). This ES is a home-built system which besides the spraying needle as the main components including two consecutive trapping stages of the produced ions before their injection into a cryogenically cooled (6 K) linear rf trap. The first trap is an octupole trap (indicated with a blue box in Fig. 4) in which the produced ions are buffer gas cooled by regular air in order to thermalize the ion's translational motion to room-temperature before injected into the second trap, a ring rf trap 1 (indicated with a red box in Fig. 4) into which an argon gas can be introduced for buffer gas cooling the ions or vibrational degrees of freedom. This latter trapping stage will also serve as a charge-to-mass selector before the ions enters the cryogenic trap. From the arrival time distribution of ions from the octupole trap (Fig.4: data points in blue), we can conclude that we can indeed cool the translational motion of the ions to temperatures close to 300 K. Likewise, we have demonstrated storage times of several hours (!) in the ring rf trap during argon buffer gas cooling (Fig.4: data points in red), which indicates there will be ample of time for internal state cooling.



4. Sketch of the main ion guiding parts of the novel ES at AU. The blue boxes indicate the position of the octupole trap and the extraction signal obtained. The red boxes indicate the ring rf trap and storage time results. *Credits: Aarhus University.*

TU Delft has continued to synthesize undoped YLF nanocrystals (NCs) for experiments carried out at UCL. The reason chosen not to dope the YLF NCs with ytterbium (Yb) ions yet is related to heating and subsequent disintegration of the NCs under the measurement conditions at UCL. Until a high enough photoluminescence quantum efficiency (QE) is reached (>95%), the introduction of Yb in the NCs increases the heating and disintegration rate of the NCs. For the most stable measurement conditions at UCL, the TUD group therefore currently does not introduce the dopant that, with a high enough QE, should lead to optical refrigeration.

To understand how and why the QE is not yet high enough TU Delft still investigates doped NCs. In collaboration with Débora Malhães and Sara Bals from EMAT, Antwerp, the group has analyzed the possibility of Yb-ion migration from the core into the protecting shell. To reduce any QE losses, the shell has to be free of any Yb-ions. From high resolution electron microscope imaging combined with elemental analysis, it has been observed that ion migration does take place and that the Yb-ions can be found back in the shell.



5. High resolution electron microscope image combined with elemental analysis indicating Yb-ion migration from the core NC to the shell. Images acquired by Débora Malhães, EMAT Antwerp. *Credits: TUDelft.*

One of the main challenges we currently face at TU Delft, and one of the topics it will focus on, is how to reduce the fraction of Yb ions in the shell of the NCs. If successful, the QE of the doped NCs may move far closer to the required QE for optical refrigeration. In the meantime, the TUD group will keep supplying UCL (and when requested other TEQ-partners) with doped and undoped NCs, to ensure the TEQ-studies can be continued as good as possible.

Quantum field theory is completely characterized by the field correlations between spacetime points. In turn, some of these can be accessed by locally coupling to the field simple quantum systems, also known as particle detectors. In a recent Physical Review Letters (Phys. Rev. Lett. 125, 131602, 2020) the **Vienna node** considered what happens when a quantum-controlled superposition of detectors at different space-time points is used to probe the correlations of the field. It was shown that, due to quantum interference effects, two detectors can gain information on field correlations that would not be accessible, otherwise. This has relevant consequences for information theoretic quantities, like entanglement and mutual information harvested from the field. In particular, the quantum control allows for extraction of entanglement in scenarios where this is, otherwise, provably impossible. In the next period, the OEAW group plans to apply the technique of quantum reference frames to describe quantum systems in a superposition of spacetimes.

PUBLICATIONS

To explore the latest publications, visit [Publications | TeQuantum](#).

DISSEMINATION ACTIVITIES

In the last 3 years (since the beginning of the project in January 2018), the dissemination activities held were a total of 257, addressing over 16 000 people in 30 different countries.
Here below a highlight of some outstanding dissemination activities during 2020 per partner:

- OEAW (Caslav Brukner): "*Timeless formulation of Wigner's friend scenarios*" at the The Quantum Information Structure of Spacetime Workshop, The Hong Kong University, January 2020 – 25 participants;
- UoS (Hendrik Ulbricht): "*Proof-of principle experiments for QT in space*" at the QTSpace school, Ljubljana, Slovenia, February 2020 – 30 participants:
- QUB (Alessio Belenchia): "*Informational Content of the Gravitational Field of a Quantum Superposition*", online mini-workshop on Quantum Gravity Phenomenology, April 2020 – 50 participants;
- TUDelft (Jence T. Mulder): "*Uses, optical properties and synthesis of 0D and 3D nanomaterials*" at 3ME faculty, May 2020 – 40 participants;
- UniTs (Angelo Bassi): "*Collapse models*" webinar, July 2020, 50 participants;
- INFN (Catalina Curceanu): "*La trama dell'Universo: dalla relativita' di Einstein ai misteriosi Buchi Neri*" at Liceo Classico Plauto, Rome, August 2020 – 135 participants;

A detailed list of all talks can be found at Talks | TeQuantum.

CHANGES AND NEWS WITHIN THE TEAMS

At UNITS Caitlin Jones and Lorenzo Asprea have completed their PhD. Michele Vischi, a new PhD student has joined the Trieste team.

Christopher Timberlake from the University of Southampton has successfully completed his PhD and successfully defended his thesis. He remains as a post-doc in the group and works on the TEQ project. During his PhD on the TEQ project he has published six scientific papers in peer-reviewed journals and two of those as the lead author.

Within the Belfast node, Luca Mancino left the research group while Giorgio Zicari has been newly appointed.

To find the list of TEQ's past members, please visit the new section of the TEQ website Past members | TeQuantum.

ANY OTHER RELEVANT INFORMATION

Outreach activities

On October 15, 2020, Dr Catalina Oana Curceanu participated, together with Roberta Fulci, speaker for *Radio3 Scienza*, at the third day of the cycle of meetings "*Scienza, coscienza e conoscenza. Sei sguardi ai saperi per* fare *comunità*" aimed at bringing science to the general public. The meetings were organized by *ERT Fondazione* in collaboration with *Fondazione per l'Innovazione Urbana* e *Rai Radio3 Scienza.* Dr Curceanu presented the basics of quantum mechanics, the concepts of superposition of states and entaglement, problems connected to quantum mechanics and possible solutions (parallel worlds, new theories or something else?), showing how quantum properties could generate a fundamentally different technology.

Seminar series on optomechanics by UoS

TEQ member Professor Hendrik Ulbricht is involved in setting up and running the UniKORN online seminar series on optomechanics, which is strongly linked to the TEQ project. The goal of UniKORN is to bring together researchers working on all sorts of optomechanics theory and experiments within the United Kingdom, as part of the British Optomechanics Research Network (BORN) and beyond. BORN aims to strengthen the strategic role of optomechanics amongst the emerging quantum technologies (QT), but is not limited to the quantum side of optomechanics. UniKORN particularly fosters and supports early career researchers and give a platform for them to present their latest research results. UniKORN is open and inviting to everyone to join for the weekly seminars, registration can be found on the UniKORN webpage: https://www.optomechanics.net/?page_id=83
UniKORN has been adapted to have scientific interactions under Covid-19 by holding online events, but will hopefully soon be able to organize also in-person scientific workshops and events.

"Is quantum theory exact?" A TEQ-supported workshop

The aim of the workshop is to discuss the possible boundaries and limits of validity of the quantum mechanics theory and the implications of this research in various sectors. From the theoretical point of view, since the famous Einstein-Bohr debate, quantum mechanics never stopped raising deep questions about its meaning. In particular, the transition from the microscopic world, where systems are observed in a superposition of quantum states, to the macroscopic world, where systems have well defined properties, such as position (the so-called "measurement problem"), still puzzles the scientific community and philosophers. For this reason, (some) scientists are pushed to look for explanations, including theories beyond the standard quantum one.

From the experimental point of view, quantum mechanics is, undoubtedly, the best verified available theory and a pillar to all our science. It is therefore a very compelling challenge to look for possible small violations predicted by alternative quantum theories. The aim is either to put stronger observational bounds on the new theories, i.e. on model's parameters, or, much more exciting, to find a violation of standard quantum mechanics when compared with the new theories' predictions. In this framework, a deeper understanding of the possible limits of validity of the quantum superposition principle is an interesting experimental challenge.

The workshop took place online from December 10 9:00 am to December 11 6:00 pm. Details can be found at "Is quantum theory exact?" A TEQ-supported workshop | TeQuantum.

Follow-up meeting on TEQ experiment

TEQ experimentalists have met on November 23, 2020 to update on developments of setting up the low-noise electronics, update on particle loading experiments at UCL & AU, and evidence for decision on details for realization of the ultimate experiment at Southampton. This is the follow up meeting after June 2020 on experiments.
More info at Follow-up meeting on TEQ experiment | TeQuantum.