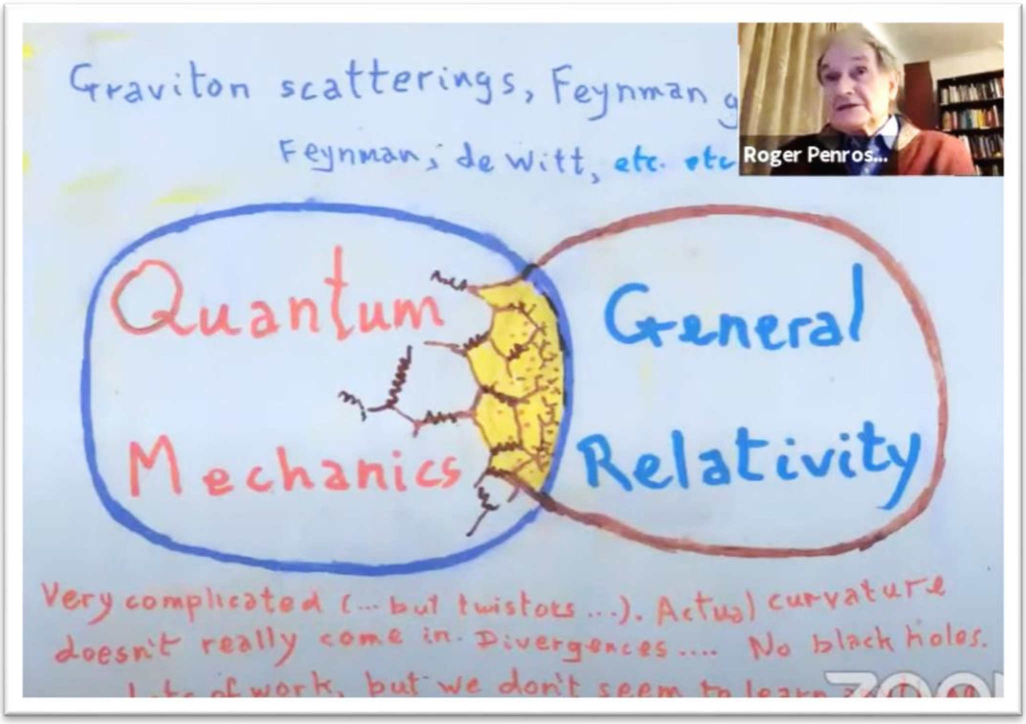
NEWSLETTER N.13, June 2021



Nobel Prize for Physics Prof. Sir Roger Penrose (University of Oxford) kicked off the Laws of Nature Series seminars co-organized by TEQ PI Prof. Angelo Bassi (UniTs) on April 8, 2021 with the talk "How the Large and Small Interrelate in General Relativity and Quantum Mechanics".

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UPDATE OF WORK DONE

In the research on the interplay of quantum theory with gravity, **UNITS** developed a dissipative treatment of two models describing gravity as fundamentally classical and mediated by a classical stochastic channel. These models, without such a dissipative treatment, predict the energy divergence of the system's energy. Conversely, with our generalization, we showed that the system can thermalize to an effective temperature.

Moreover, in collaboration with QUB, UoS and other collaborators, UNITS studied possible implementations of experiments testing collapse models in space. The first one is strictly related to the possibilities of performing tests of the quantum superposition principle with particles of nanometer size in space. The second one is part of a larger project whose general focus are the employment of quantum technologies in space.

The activity of the **LNF-INFN** group was in part dedicated to continue to support the UCL staff for the use of the low-noise electronics developed by LNF, which is presently in use at UCL. This activity was realized via online meetings and virtual work with UCL colleagues, and was focused on reducing the electronic noise on the overall setup. As a result of these tests the realization of a signal generator was resulting as an important element of the setup.

The LNF team studied and developed a low-noise and low-distortion (Max THD -110dB) signal generator at fixed frequency with possibility to vary the amplitude; a first prototype was realized and successfully tested. The outcome was discussed with UCL partner. Presently, the development of a unique electronic block that puts together the power supply, signal generator, amplification and signal mixing functions, is undergoing. Other features are under study.

The group continued the development of tools for refined statistical analyses methods of the data.

The **QUB** team has recently put forward an approach to the investigation of potential effects due to the occurrence of collapse mechanisms based on the use of Baesyan hypothesis testing. The protocol makes use of squeezed light to enhance the performance of the test itself, applying it to a canonical optomechanical setting. Input squeezed noise and feasible measurement schemes on the output cavity modes, allow to obtain an advantage with respect to any comparable classical schemes. Our initial study addressed the case of continuous spontaneous localisation (CSL), and we are now expanding this investigation along the lines of addressing the Diosi-Penrose model, as well as the dissipative version of CSL. The scope of our study is to show that the combination of an information theoretic approach and sophisticated statistical analysis tools provide powerful methods for the discrimination of the fine-grained structure of different collapse models. We are also comparing the performance of the scheme to what has been achieved in the past by the group, in a collaboration with Southampton and Trieste, using quantum parameter estimation. Along different, yet related lines, QUB is working with the experimental group led by Kiesel and Aspelmeyer on the characterisation of localisation effects in a levitated nanoparticle trapped in a time-dependent potential. We are explicitly addressing the problem of a switch from quadratic to double-well potentials and the influence that localisation mechanisms have on the dynamics of the particle. In particular, we are characterising the entropy production resulting from the switching and we will add the effects collapse mechanisms on the evolution of the mechanical system in a second phase of the investigation.

Over the last period the UCL team have focused primarily on characterising noise in the Paul trap electronics and the rotational motion of the trapped YLF particles supplied by TUDelft.

We have now shown that there is no measurable heating of trapped nanoparticles in the Paul trap when operating down to our current vacuum limit of 10^-7 mbar. This has come about via collaboration between the UCL and Frascati team to minimise noise that was introduced in connecting all parts of the system. Based on this work, and with further improvement from the Frascati team, we expect that the force noise limits required by TEQ can be met in the Paul trap when operating with a low number of charges on the trapped nanoparticle.

The characterisation of the dynamics of undoped YLF particles has continued and we can now model the dynamics of the particles' motion as observed in the optical trap. This includes the translational motion, but also the different gas damping measured in these modes. The rotational motion and damping is very sensitive to the particle shape and analysis of this motion appears to be a promising method for determining this property.

Publications resulting from the programme over this time period include *Performance limits of feedback cooling methods for levitated oscillators: a direct comparison*, T. W. Penny, A. Pontin, P. F. Barker, arXiv:2102.01060 (2021); *Quadratic Optomechanical cooling of a cavity-levitated nanospher*, N. P. Bulliger, A. Pontin, P. F. Barker, arXiv:2006.1620 (2020), accepted for Publication in Physical Review Research.

At Southampton, we have been busy with preparing and performing magnetic levitation experiments. We have used a setup at 4 K for testing different trap geometries and particles of different sizes. We have investigated the lead surfaces and how to prepare those smoothly and cleanly as this is crucial for trapping particles of size smaller than 10 micrometer. We have made good progress and will push for experiments testing CSL models in the 300 mK cryostat now. We have designed and planned specific vibration dampers to be included inside the cryo to filter mechanical noise at the trap frequency for decreasing such noise limits in the experiments together with experts from Leiden University and CNR Trento. We had a number of meetings with TEQ partners to discuss the further testing and implementation of analogue electronics for the Paul ion trap. The Paul trap is an alternative for testing CSL noise, and we are considering it still for the ultimate experiment at 300 mK. We have also discussed and theoretically investigated the measurement protocol for using low frequency data to test CSL noise. There appear to be prospects even for experiments at room temperature. There are a number of promising options for the ultimate TEQ experiment, and we are progressing along those, step by step.

We have further developed a theoretical model and proposal to test for non-Newtonian gravity based on levitated magnetic mechanics with two particles. We have written a proposal paper and submitted a grant proposal with collaborators from the astronomy and theory departments at Southampton. Together with collaborators in Germany, we have analysed the dynamics of levitated magnets for the ultra-precise detection of magnetic fields and a paper on the topic has been written and submitted to a journal.

In the recent months, the **AU** partner has performed resolved sideband spectroscopy of a single trapped and Doppler laser cooled Ba^+ ion. These experiments were done in the cryogenically cooled ion trap eventually to be applied in experiments with a co-trapped and sympathetically cooled single highly charged complex molecular ion (see more in Newsletter #11). The spectroscopy is carried out on the ultra-narrow 6s $^2S_{1/2}$ – 5d $^2D_{5/2}$ quadrupole transition at 1762 nm to be used for resolved sideband cooling of a single Ba^+ ion to its motional ground state (See Fig. X.a). To close the spectroscopy cycle much faster than the 32 s lifetime of the 5d $^2D_{5/2}$ state, after a spectroscopy pulse of 20 ms and following state detection, the ion is pumped back to the 5s $^2S_{1/2}$ state via excitation on the much stronger 5d $^2D_{5/2}$ – 6p $^2P_{3/2}$ dipole allowed transition followed by spontaneous decay. The state detection is carried out by having the ion exposed to laser light at 494 nm and 650 nm to drive the 6s $^2S_{1/2}$ – 5p $^2P_{1/2}$ and 5d $^2D_{3/2}$ – 5d $^2P_{1/2}$ transitions, respectively, and monitor the potential fluorescence. If fluorescence is observed, we know the ion did not make a transition by the spectroscopic laser pulse, while if no light is detected the ion must have made a transition into the 5d $^2D_{5/2}$ state. In Fig. X.b. resolved sideband spectra are presented for two values of the ion's motional frequency. By this experiment the carrier transition is easily identified by the stationary dip. With this knowledge, we are now ready to perform sideband cooling of a single Ba^+ ion.

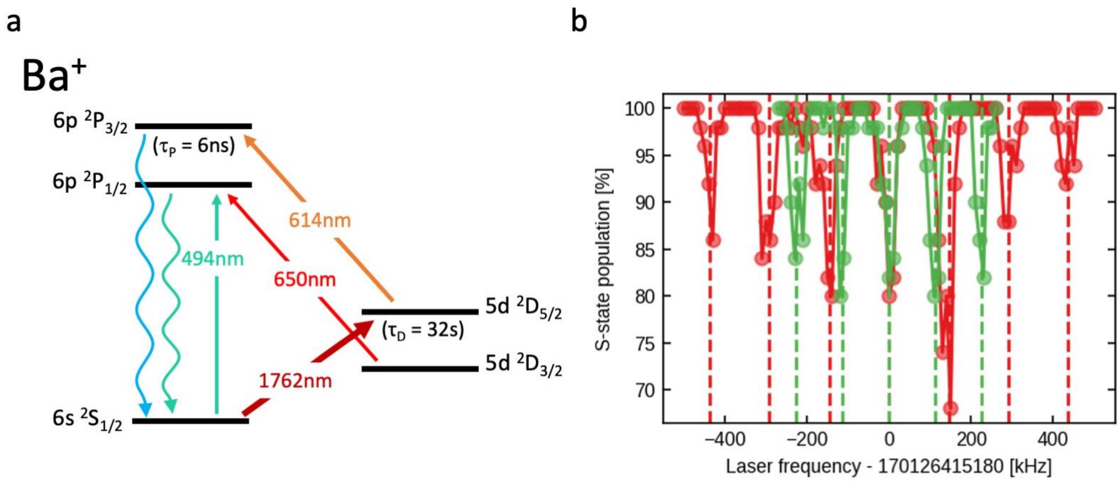


Figure 1. **a.** Level diagram of the Ba+ ion including the main relevant laser driven (straight lines) and spontaneous emission (wavy lines) transitions in the experiments. **b.** Motional sideband resolved spectra of the 6s 2S1/2 – 5d 2D5/2 quadrupole transition at ~170 THz for trap frequencies of 113 kHz (green) and 146 kHz (red), respectively. The vertical dashed lines indicate the expected position of the various sidebands.

In the last months, at **TU Delft**, the group has been working hard to be able to publish an article titled: "Electrochemical p-Doping of CsPbBr3 Perovskite Nanocrystals" in ACS Energy Letters (https://pubs.acs.org/doi/10.1021/acsenergylett.1c00970). After a number of years, which included publications describing the overall limits, this was the first publication where hole injection into the valence band of these nanocrystals (NCs) was proven. Therefore, this paper might be of great interest in the field of perovskite NCs.

In parallel, work has continued on synthesizing Yb:YLF NCs. The main challenge, obtaining a high enough photoluminescence quantum yield (PLQY) for the emission of the NCs to observe optical refrigeration (PLQY<97.5%), is unchanged. While undoped YLF NCs can be made of high quality, and can be captured stably in the optical trap at UCL, all Yb:YLF NCs are unstable due to heating, which is a result of the too low PLQY. In the last months, we have especially investigated the growth of high quality undoped YLF shells around Yb:YLF cores. We are now close to controlling this process, and synthesizing the preferred core-shell NCs, something that was found to be more difficult than anticipated. With this knowledge, we aim to unravel the PLQY quenching pathways and to subsequently removing these to obtain highly luminescent Yb:YLF NCs.

One of the most fundamental open problems in physics is the unification of general relativity and quantum theory to a theory of quantum gravity. An aspect that might become relevant in such a theory is that the dynamical nature of causal structure present in general relativity displays quantum uncertainty. This may lead to a phenomenon known as indefinite or quantum causal structure, as captured by the process matrix framework. A popular approach towards a quantum theory of gravity is the Page-Wootters formalism, which associates to time a Hilbert space structure similar to spatial position. Within the **Vienna node (OEAW)**, the group combined the process matrix framework with a generalization of the Page-Wootters formalism in which one considers several observers, each with their own discrete quantum clock. It was described how to extract process matrices from scenarios involving such observers with quantum clocks, and analyzed their properties. The description via a history state with multiple clocks imposes constraints on the physical implementation of process matrices and on the perspectives of the observers as described via causal reference frames. While it allows for describing scenarios where different definite causal orders are coherently controlled, the group explained why certain non-causal processes might not be implementable within this setting.

PUBLICATIONS

Authors	Title	Journal	Volume	Pages	Year
Mulder, Jence T., Indy du Fossé, Maryam Alimoradi Jazi, Liberato Manna, and Arjan J. Houtepen	Electrochemical p-Doping of CsPbBr 3 Perovskite NanocrystalsElectrochemical pDoping of CsPbBr3 Perovskite Nanocrystals	ACS Energy Lett.	XXX	2519–2525	2021
Asprea, L., A. Bassi, H. Ulbricht, and G. Gasbarri	Gravitational Decoherence and the Possibility of Its Interferometric Detection	Phys. Rev. Lett.	126	200403	2021
Fadeev, Pavel, Chris Timberlake, Tao Wang, Andrea Vinante, Y B. Band, Dmitry	Ferromagnetic gyroscopes for tests of fundamental physics	*Quantum Sci. Technol.*	6	024006	2021

Budker, Alexander O. Sushkov, Hendrik Ulbricht, and Derek F. Jackson Kimball					
Lucas F. Streiter, Flaminia Giacomini, and Časlav Brukner	Relativistic Bell Test within Quantum Reference Frames	Phys. Rev. Lett.	126	230403	2021
J. L. Gaona-Reyes, M. Carlesso, and A. Bassi	Gravitational interaction through a feedback mechanism	Phys. Rev. D	103	056011	2021
Matteo Carlesso, Hamid Reza Naeij, and Angelo Bassi	Perturbative algorithm for rotational decoherence	Phys. Rev. A	103	032220	2021
Simone Rijavec, Matteo Carlesso, Angelo Bassi, Vlatko Vedral and Chiara Marletto	Decoherence effects in non-classicality tests of gravity	*New J. Phys.*	23	043040	2021

To explore the latest publications, visit Publications | TeQuantum.

DISSEMINATION ACTIVITIES

In the second quarter of 2021, TEQ members delivered online seminars and talks to a total of 2.820 people in audience:

Who	What	Where	When
Catalina Curceanu	Alla scoperta del computer quantistico	Le Vie Della Scienza (Velletri 2030)	March, 2021
Angelo Bassi	Meccanica Quantistica	Seminar	March, 2021
Angelo Bassi	Present and future precision tests of spontaneous wave function collapse models	Photonics West	March, 2021
Angelo Bassi	The Trouble with Quantum Mechanics… and a possible solution	APS March Meeting 2021	March, 2021

Angelo Bassi	Tests of Quantum Mechanics	ECFA Detector & Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies	April, 2021
Angelo Bassi	Sofisticate Realizzazioni della Meccanica Quantistica, la nuova frontiera dell'innovazione tecnologica?	Seminar	April, 2021
Angelo Bassi	Wave Function Collapse & Gravity	Workshop "The Quantum & The Gravity"	April, 2021
Catalina Curceanu	Meccanica Quantistica nel silenzio Comsico	Online Seminar	April, 2021
Catalina Curceanu	Underground tests of Quantum Mechanics Gravity-related and CSL wave function collapse models	Online colloquium	April, 2021
Catalina Curceanu	Alla scoperta del Regno Quantistico e delle sue meraviglie	Talk at Liceo Landi	April, 2021
Angelo Bassi	Present and future precision tests of spontaneous wave function collapse models	Seminar at the University of Bern	May, 2021
Catalina Curceanu	Quantum mechanics under test in the underground laboratory of Gran Sasso	Invited colloquium	May, 2021
Angelo Bassi	Il mondo dei Quanti	Seminar	June, 2021
Luis Cortés Barbado	Quantum Foundations, Information and Technology Seminar (QuFITS), University of York	Quantum Information Seminar: Transformation of Spin in Quantum Reference Frames	June, 2021
Catalinea Curceanu	Dall'incredibile gatto di Schrödinger alle tecnologie quantistiche	Online Seminar	June, 2021
Marta Maria Marchese	Quantum Hypothesis Testing for Collapse Models using an Optomechanical Setup	Talk at Universita' degli Studi di Palermo	June, 2021
Marta Maria Marchese	Quantum Hypothesis Test for Collapse Models	Theory Coffee talks	June, 2021
Angelo Bassi	Quantum Mechanics: what is it about?	Seminar	June, 2021

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

ANY OTHER RELEVANT INFORMATION

Laws of Nature Series kicks off with Nobel Roger Penrose

Laws of Nature Series is a new initiative to promote the exchange of physical, philosophical, and mathematical ideas in the field of the foundations of quantum physics. The *Laws of Nature Series* comprises a Spring and Autumn Series each comprising monthly online colloquia held in the form of themed sessions on Zoom.

Currently, this initiative is organized by

- Angelo Bassi from the University of Trieste,
- Dirk - André Deckert from the LMU Munich, and
- Ward Struyve from the KU Leuven.

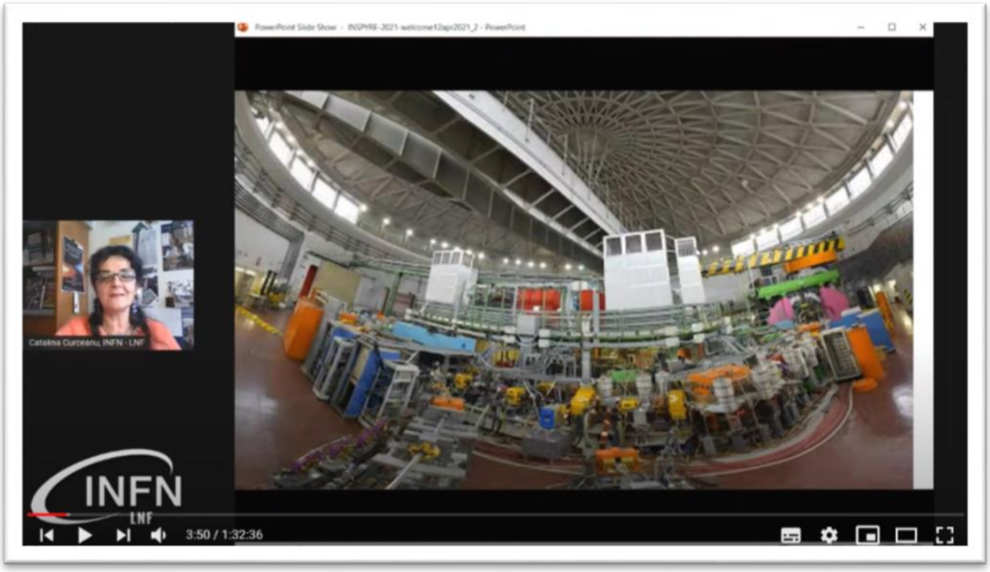
The initiative was kicked off on April 8, 2021 by the Nobel Laureate in Physics Professor Sir Roger Penrose (University of Oxford) with the talk "How the Large and Small Interrelate in General Relativity and Quantum Mechanics". The event was attended by 650 people, both on live on Zoom and on the YouTube livestream.

The Series went on with:

06.05.2021, 16:00 CEST (Brussels time)	Robert Wald & Michael Kiessling	▶ Wald: Point Particles and Self-Force in Electromagnetism ▶ Kiessling: Revisiting the 1920s --- with the benefit of hindsight
03.06.2021, 16:00 CEST (Brussels time)	Francesca Vidotto & Stefano Liberati	▶ Vidotto: If you want to build a universe from scratch you must first invent a quantum state of the geometry ▶ Liberati: Hearts of Darkness: probing of black holes inside out
01.07.2021, 16:00 CEST (Brussels time)	Siddhant Das & Sandro Donadi	▶ Das: Can we fix quantum arrival times before 2026? ▶ Donadi: Collapse Models: State of the Art and Future Perspectives

More info on Laws of Nature Series [Laws of Nature Series (laws-of-nature.net)](laws-of-nature.net).

INSPYRE 2021 – INternational School on modern PhYics and REsearch



The group LFN-INFN organized the INSPYRE 2021 International School for high-school students (online) which was supported by TEQ and where a talk was given by C. Curceau and H. Ulbricht on Quantum Mechanics and TEQ project.

More info on [INSPYRE 2021 | Educational (infn.it)]

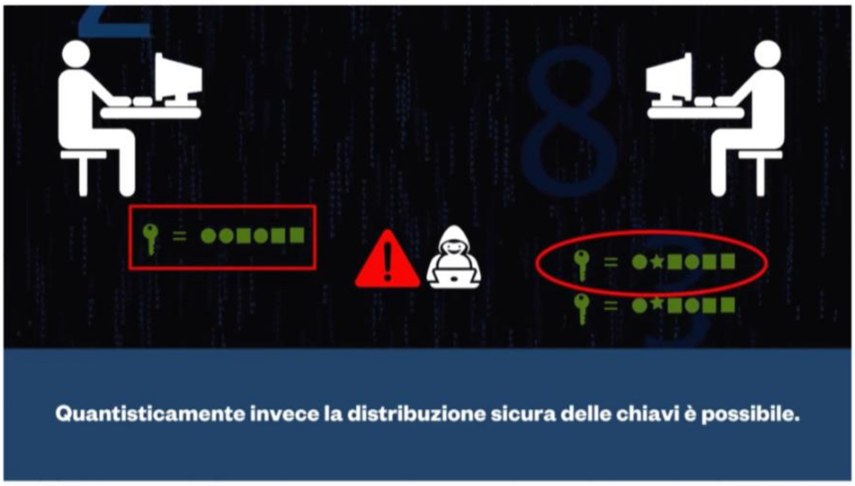
Towards new Quantum mechanics: an interview on Le Scienze

Because of the growing international success of the [study published last September in Nature Physics], Prof. Angelo Bassi (University of Trieste) was interviewed by the monthly magazine *Le Scienze*, April 2021 issue. In the interview, entitled "Towards new Quantum mechanics", Bassi explains the issue of measurement of Quantum systems and models of spontaneous wave function collapse that identify a precise cause that can determine what happens to a Quantum system before its measurement. The interview deepens the research work published in Nature Physics, which tested a model proposed by Nobel Laureate Roger Penrose, according to which the force of gravity is the cause of the collapse of the wave function. As we know, this model, in its simplest formulation, has been invalidated by the experiments conducted at the Gran Sasso Laboratories by colleagues of the Italian Institute of Nuclear Physics (INFN). Bassi concludes the interview with a reflection on the ambitions of the TEQ project which aims, with a large funding from the European Commission, to experimentally investigate the theoretical predictions of some models of spontaneous wave function collapse. "This interview represents another great acknowledgement of the work that has been done in the past years", says Prof. Bassi.

Quantum communication: an Italian public demonstration

The security of communications is a pivotal aspect to ensure the authenticity, integrity and confidentiality of the information that is exchanged daily across the Web. In today's world, that functions thanks to the exchange of information via the Internet, the security of communications is one of the main priorities for the public as well as for the private sector and for individual citizens. Different security methods are used depending on the required level of security. The safest method uses two copies of an identical cryptographic key — basically a random sequence of numbers — that are owned by both the sender and the recipient of the message, and can be used only once. However, there is a problem: How can sender and recipient share the same key without creating a security risk? Traditionally the best option is to trust the human or electronic courier in charge of transmitting the key.

Quantum technologies can solve this problem. Whereas normally it is possible to intercept the key and copy it while the sender and the recipient remain unaware of the security breach, this is not possible if they are using quantum keys. Any attempt to make a copy of a quantum key causes the key to change, which can be easily noticed by the recipient by simply comparing parts of the two copies.



Comunicazione quantistica: una dimostrazione UNITS e CNR-INO ad ESOF2020 (Trieste)

In the field of quantum communications, Italy is at the forefront and several Italian research groups have already achieved very important results.

During the closing ceremony of ESOF2020 (EuroScience Open Forum), held in Trieste on September 6th 2020, the Quantum Communications group of the National Institute of Optics of the National Research Council (CNR-INO) along with the University of Trieste and the Technical University of Denmark (DTU) have publicly presented an encrypted videoconferencing system with QKD.

The quantum exchanged cryptographic key was used for a secure communication between the Rector of the University of Trieste Roberto di Lenarda, connected by the Department of Information Systems, and the then Prime Minister Giuseppe Conte, who was on the stage of the ESOF2020 Auditorium at the Porto Vecchio in Trieste.

A video-trailer, summing up the highlights of this demonstration of quantum communication, was realized by the organizers and can be viewed here.