Poster sessions

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Chapter 1

Session 1: Monday and Tuesday

1.1 (Communication) On Quantum Fingerprinting and Hashing

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Fingerprinting and cryptographic hashing have quite different usages in computer science, but have similar properties. Interpretation of their properties is determined by the area of their usage: fingerprinting methods are methods for constructing efficient randomized and quantum algorithms for computational problems, while hashing methods are one of the central cryptographical primitives.

Fingerprinting and hashing methods are being developed from the mid of the previous century, while quantum fingerprinting and quantum hashing have a short history.

In this work we investigate quantum fingerprinting and quantum hashing.
In the talk we present computational aspects of quantum fingerprinting and quantum hashing, discuss cryptographical properties of quantum hashing. The talk is based on the results of the paper Farid Ablayev and Marat Ablayev "On quantum fingerprinting and quantum hashing". The Article available at https://www.intechopen.com/books/advanced-technologies-of-quantum-key-distribution/on-quantum-fingerprinting-and-quantum-cryptographic-hashing

1.2 (BSCC) Coherent transfer of quantum information in a hybrid platform.

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Transfer of quantum information in *hybrid platforms* is an urgent problem whose solution requires combining different systems and technologies with a multidisciplinary approach. Here, in order to read out and transfer quantum states between different types of *spin systems*, we exploit both direct magnetic coupling and long-range interactions mediated by microwave (MW) photons confined in *superconducting circuits.* Due to their tunability and integrability in solid state platforms, we focus on prototypical spin systems that show great potentials as quantum sensors and registers: *molecular spins* [1] and quantum dot systems realized with *semiconductor nanowires.* I shall present our recent achievements on their effective integration in superconducting circuits and, more specifically, in reaching their coherent coupling with microwave photons in planar resonators [2]. To monitor molecular spin performances over a wide temperature and magnetic field range we have first developed microwave planar resonators made of high-Tc (YBCO) superconductors, obtaining excellent performances up to liquid Nitrogen temperature and magnetic fields up to 7 Tesla [3]. Ensembles of different molecular spin systems have been systematically tested. The regime of high spin-photon cooperativity is achieved with molecular spins diluted in non-magnetic matrix at 0.5K [4], while the strong coupling regime is observed with concentrated samples of organic radicals up to 50 K [3,5]. The possibility to create coherent states among distinct spin ensembles [5] or to coherently couple two microwave photons through a spin ensemble [6] is further explored in similar spectroscopic and MW-pulsed experiments. Further development of such hybrid platform also comprising semiconducting nanowires will be also presented.

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1.3 (Sensing) NV center based nano-NMR enhanced by deep learning

Nati Aharon [1], Amit Rotem [1], Liam P. Mcguinness [2], Fedor Jelezko [2], Alex Retzker [1], Zohar Ringel [1]

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The growing field of nano-NMR seeks to estimate spectra or discriminate between spectra of minuscule amounts of complex molecules. While this field holds great promise, nano-NMR experiments suffer from adverse inherent noise. In this work [1] we present strong indications that deep learning algorithms can efficiently mitigate the adversarial effects of noise. We show that this approach outperforms Bayesian methods even when the latter have full pre-knowledge of the noise model and the former has none. These the deep learning algorithms also emerge as much more efficient in terms of computational resources and run times. On the basis of various real-world scenarios in which the noise is complex and difficult to model, we argue that deep learning is likely to become a dominant tool in the field.

[1] Nati Aharon, Amit Rotem, Liam P. McGuinness, Fedor Jelezko, Alex Retzker, and Zohar Ringel, arXiv:1809.02583

1.4 (Communication) High efficient coupling of nano emitters with integrated optical waveguides

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In the last few years, the excitation of light sources has been successfully implemented using several integrated optical devices within a few nanometers. For example, the excitation of nano-emitters has been realised by surface plasmon polaritons (SPPs) in nano-antennas optical cavities with nanocrystals, nanowires and metallic waveguides. The used materials (silicon and noble metals) for the excitation process are characterized by high losses in the visible spectral range. Our target is how to enhance the light confinement in design integrated device using low-loss materials. Consequently, the coupling between nanostructures and waveguide will increase. Our choice has converged towards ion exchanged optical waveguides (IEW). However, the excitation of the nanostructures with this kind of waveguides is not well-spread because it has low light confinement due to the low index contrast between the core and cladding. In our work one proposal is reported to enhance the field confinement in IEW. Firstly, dielectric thin film of high index material (TiO2, SiC, ZnO, ..etc.) deposited above IEW is used to increase the light confinement inside the waveguide [11]. The hybrid modes with higher effective indices occur because of the propagation of the guided mode through the structure. Furthermore, two waveguides coupled will appear, due to excited modes of the TiO2 layer resulting from the evanescent wave of the guiding mode in IEW that will enhance the light confinement inside the IEW. The nanosource will be placed on the top of the structure and will be excited by an incident light.

Simulation results were obtained using the 3-D finite differential time domain (3-D FDTD) method. Our proposed design will enhance light guidance through the IEW due to the presence of an SiC slab. In this work, the role of the dielectric slab is studied at different thicknesses, lengths, materials and widths to get the optimum dimensions of the slab and study their impacts on enhancing the light confinement and the measured transmission. We demonstrated that the proposed structures allow increasing the measured transmission to 68%.

We will also present our recent work on coupling our waveguides with electrically excited plasmon sources.

Keywords: quantum photonics, integrated optics, ions-exchange.

1.5 (Computation) Split gate devices in silicon CMOS : tunable coupling and gate RF-reflectometry

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Since the proposal of D.Loss and D. P. DiVincenzo in 1997 [1], semiconductor-based quantum dots have been widely studied as promising platform for Quantum computing. In Grenoble, the Quantum Silicon Group [2] is pursuing the development of silicon-based spin qubits relying on industrial-scale CMOS technology. To this aim, we leverage the expertise in microelectronics at Leti and the expertise in cryogenic transport and high-frequency measurements at the INAC and Neel institutes. Recently, we reported the first silicon spin qubit issued from a 300-mm CMOS fab line [3].

Our experiments are performed on double-gate nanowire transistors with a split-gate geometry [4].The poster is organized in two parts : the first one is dedicated to the tunable coupling between two quantum dots in a silicon nanowire thanks to a backgate voltage while the second part presents new results on gate radiofrequency (RF) reflectometry for the readout of the quantum dot charge and spin states [5].

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1.6 (Communication) QGM: an Efficient Quantum Scheme for Distributed Functional Monitoring

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In distributed functional monitoring (DFM), a number of sites each observes a stream of items and communicates with one coordinator, whose goal is to compute a function of the union of the streams. In a particular DFM paradigm denoted as threshold monitoring, the coordinator wants to know if f(v(t)) > T, where v(t) is a d-dimensional binary vector that represents the state of the stream as an average of local states at the sites.
For solving this problem, we enhance the classical Geometric Monitoring (GM) method [1] with quantum communication and entanglement. The resulting method is denoted as Quantum Geometric Monitoring (QGM). We propose two QGM protocols, namely QGM-Flat and QGM-Tree. For the sake of scalability, QGM-Tree builds upon and generalizes QGM-Flat.

In QGM-Flat, the coordinator is connected to all N sites. Thanks to the properties of Bell states, the steady state communication cost, for each iteration, is statistically lower than the one of the classical setting, which is always 2dN. When N becomes too large, the performance of QGM-Flat deteriorates. For a scalable implementation, we propose to organize the sites in a tree structure. The resulting global monitoring protocol is actually QGM-Tree.

We have implemented QGM-Flat and QGM-Tree with SimulaQron [2], a novel tool enabling application development and exploring software engineering practices for quantum networking. Simulation results confirm analytical ones, on both QGM-Flat and QGM-Tree.

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1.7 (Simunlation) Quantum simulation of exotic phases of matter with interacting photons in superconducting chips

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Interacting photons in strongly coupled light-matter systems such as superconducting chips or quantum nonlinear optics media have been proposed as alternative quantum simulators for realizing Mott insulators, Fractional Hall states and Luttinger liquids of light[1,2]. The large length scales, the accessibility for local measurements and the ability of probe driven dissipative phenomena provide these systems with complementary qualities to optical lattices and ions trap setups.

We present here a recent experiment in this direction in collaboration with the Google Quantum Hardware group[3]. Using a chain of nine superconducting qubits, we implemented a technique for resolving the energy levels of interacting photons following Bose-Hubbard dynamics. We benchmarked this method by capturing the main features of the intricate energy spectrum predicted for two-dimensional electrons in a magnetic field—the Hofstadter butterfly. In the second part, we introduced disorder and studied the statistics of the energy levels of the system as it undergoes the transition from a thermalized to a localized phase. The formation of a mobility edge of an energy band was observed and its shrinkage with disorder toward the center of the bands was measured. Our work introduced a novel few-body spectroscopy technique to study quantum phases of matter that could be useful in future approaches.

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*Speaker

1.8 (Simulation) Extractable work, the role of correlations, and asymptotic freedom in quantum batteries

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We investigate a quantum battery made of N two-level systems, which is charged by an optical mode via an energy-conserving interaction. We quantify the fraction E(N) of energy stored in the B battery that can be extracted in order to perform thermodynamic work. We first demonstrate that E(N) is highly reduced by the presence of correlations between the charger and the battery or B between the two-level systems composing the battery. We then show that the correlation-induced suppression of extractable energy, however, can be mitigated by preparing the charger in a coherent optical state. We conclude by proving that the charger-battery system is asymptotically free of such locking correlations in the N $\rightarrow \infty limit$

1.9 (BSCC) Magnetoroton in a binary Bose-Einstein condensate with soft-core repulsion

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During the past years binary mixtures of superfluids have attracted an ever-growing amount of interest. In addition to the total density fluctuations, a mixture also has out-of-phase fluctuations of its components (spin waves). In our recent paper [1] we (and a master student of one of us) have generalized the Bogoliubov method of calculation of the excitation spectrum to account for the "quantum friction" between the components (Andreev-Bashkin entrainment effect). In the present work [2], we demonstrate the power of this method on the model system of "soft spheres" - particles with soft-core interactions. We predict the following new phenomena:
Spin waves may become self-localized due to the entrainment effect. This provides a new mechanism for the phase separation of the components (de-mixing);

We predict a roton in the spin-wave dispersion, which we call *magnetoroton.* We show a direct analogy of this roton to a Bose polaron, which implies a possibility of a *roton self-localization.* The latter is governed by a macroscopically large core of the roton wavefunction, which, as we argue, corresponds to the microscopic core of the Feynman ring in He. The roton self-localization, in turn, should result in formation of a *magnon crystal.* This links the Feynman picture to the state-of-the-art view of a roton as a precursor of crystallization and suggests a fundamental duality between the crystalliization phenomena in superfluids and the physics of Bose polarons.

The soft-sphere gas was predicted to be feasible experimentally, and it is a favourite model of the vast community of scientists performing numerical simulations. Qualitatively, our predictions apply also to dipolar Bose mixtures, which start being produced with ultra-cold atoms [3] and excitons in semiconductor heterostructures [4].

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The work has been supported by Russian Science Foundation (Grant No. 18-72-00013)

1.10 (Sensing) The Qonstrictor: a compact, low threshold squeezed light system

Jens Arnbak [1], Christian Scheffmann Jacobsen [1], Rayssa Bruzaca De Andrade [1], Xueshi Guo [1], Jonas Schou Neergaard-Nielsen [1], Ulrik Lund Andersen [1], Tobias Gehring [1]

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The Heisenberg uncertainty principle poses a fundamental limit to the precision with which, one can know two complementary variables of a quantum system simultaneously (e.g. position/momentum). The coherent state of a laser beam (and the quantum state of vacuum) minimizes the Heisenberg uncertainty relation, and this leads to an intrinsic noise source in light based experiments, the photon shot noise, that limits the sensitivity in optical quantum metrology experiments, e.g. gravitational wave-detection.
The limit set by the shot noise can be partially circumvented by using certain quantum states of light called squeezed vacuum, where entangled pairs of photons exhibit noise below shot noise of light in one variable and noise above the shot noise level in the conjugate variable.
Squeezed light also plays a fundamental role in continuous variable measurement-based quantum computing protocols and in certain types of continuous variable quantum cryptography protocols.
We have built a compact 1550 nm squeezed state setup that fits into a 19" rack. The compact size of the system is achieved by replacing the bulky free-space optical components with high-end fiber counterparts and using a wavelength-conversion waveguide module to supply the 775 nm pump. The setup currently generates more than 6 dB squeezing at 1550 nm via degenerate spontaneous parametric down-conversion in a double resonant, hemilithic optical parametric oscillator (OPO) using a periodically poled potassium titanyl phosphate (PPKTP) crystal as the non-linear medium. The double-resonance of the OPO ensures a very low pump threshold power of only 5 mW at 775 nm. The end-goal of the project is a portable, boxed-up system capable of delivering squeezing via a polarization maintaining fiber output.

1.11 (Communication) Diamond Group 4 Colour Centres: Transform-limited photons from diamond spins for quantum networks

Mete Atatüre [1], Benjamin Pingault [1], Mustafa Gundogan [1]

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Spin-photon interfaces are of central importance in physical implementations of quantum networks and distributed quantum computation applications. Diamond is a suitable platform to host such systems and the nitrogen-vacancy (NV) centre is arguably the most promising candidate to form the nodes of a quantum network. The key challenge for the NV centre is to overcome the poor optical properties of the photons, despite the impressive spin properties fo this centre. Group IV (G-IV) colour centres have emerged recently as alternative systems that provide an optically accessible spin together with narrow linewidth and bright optical transitions. In this talk, I will present the promising photonic and spin properties of the G-IV centres, with particular emphasis on the silicon vacancy (SiV) and tin-vacancy centre (SnV) in diamond. I will highlight the optical properties of the SiV centre and the immense tunability of emission through nano-electro-mechanical control[1], as well as its spin properties[2]. Then, I will shift focus to the SnV centre[3]: first verify that the electronic structure of SnV is very similar to other G-IV colour centres. We then show that the photons from the SnV are in the Fourier transform limit. Finally, we measure electronic spin lifetime longer than the other G-IV colour centres. Our results position the Group-IV centres as the strongest candidate to challenge the NV centre for the next generation of long-lived optical quantum nodes in a diamond-based quantum network.

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1.12 (BSCC) Toward entangled photon-pair production with hybrid nonlinear/plasmonic nanoantennas

Guillaume Laurent [1], Nicolas Chauvet [1], Gilles Nogues [1], Aurélien Drezet [1], Guillaume Bachelier [1]

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Although nonlinear photonics addresses many applications in the field of quantum optics, the realization of devices at the nanoscale raises major challenges. Reducing the size of a medium to a few tens of nanometers dramatically drops its optical nonlinear response. Among the different strategies that can be adopted to compensate that loss of efficiency, we chose to enhance the local fields with plasmonic nanoantennas. Such structure response depends on their shape, the presence of substrate, but also the tight focusing generally used, so that an in-depth investigation requires efficient numerical tools. If simulations relying on a classical description are sufficient for up conversion processes, such as second harmonic generation (SHG), a quantum approach is required for the investigation of entangled photon pair production via spontaneous parametric down conversion (SPDC), where quantum fluctuations play a major role. In this context, we have developed new simulation tools mixing quantum formalisms and numerical approaches solving Maxwell's equations for investigating hybrid nanostructures. This allows a quantitative evaluation of the photons pair production yield in realistic experimental configurations. We demonstrate, for the first time, that photon pair creation is achievable in plasmonic nanostructures holding a nonlinear nanocrystal, under realistic experimental configurations. We show how plasmonic resonances tailor the SPCD spectral response and replace the phase-matching condition at the nanoscale. Optimized photon pair production rates are obtained by tuning the antenna morphology for a given excitation and emission wavelength, yielding doubly resonant nanostructures. Huge (hundred- to thousand-fold) SPDC enhancement factors are reached by matching the nonlinear nanocrystal size with the near-field spatial distribution. As a consequence, a trade-off must be found between large enhancements and large emission rates, as the latter are intrinsically driven by the squared crystal volume. This work paves the way for investigating entangled photon pair generation at the nanoscale for an ultimate integration of quantum information and cryptography devices.

1.13 (BSCC) Controlling multi-exciton states in monolayer WSe2

Matteo Barbone [1], Alejandro R.-P. Montblanch [1], Dhiren Kara [1], Carmen Palacios-Berraquero [1], Alisson Cadore [1], Sefaattin Tongay [2], Gang Wang [1], Andrea C. Ferrari [1], Mete Atatüre [1]

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Atomically thin transition metal dichalcogenides (TMDs) have recently shown great potential as next- generation-solid-state platform for scalable, on-chip quantum photonic circuits [1]. Due to their dimensionality, they operate at the fundamental limit of single-layer thickness[2], foreseeing high photon emission rate and enabling integration with conventional silicon technology such as coupling to waveguides[3]. Furthermore, two-level systems in TMDs can be created deterministically[4] and single photons can be generated by electroluminescence[5]. They also possess Coulomb-mediated many-body interactions that result in a wide variety of free and localized exciton complexes, such as excitons and trions. Biexcitons, a two-exciton molecule[6], hold great interest from a fundamental standpoint as the simplest building block for coherent multi-exciton phenomena and for applications such as sources of entangled photons[7]. Previously, signatures of free biexcitons have been reported in TMDs[8], but limited spectral quality of the samples combined with the lack of electric and magnetic control have so far prevented their understanding and controlled access. Here we report direct experimental evidence of two biexciton complexes in monolayer WSe2, identifying and controllably accessing the neutral biexciton and the five-particle negatively charged biexciton via a combination of polarization resolved, gate-controlled and magnetic-field dependent PL measurements[9]. These results are pivotal for the development of deterministic and electrically addressable novel quantum photonic circuits.

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1.14 (Computation) Scalable micro ion traps for applications in quantum simulation and quantum computing

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Scaling quantum logic operations to a large number of qubits is a formidable challenge in any physical system. Miniature surface-electrode trap arrays built up from a library of trap components are a scalable implementation for the trapped-ion system. Microwave-driven quantum logic [1], holds the promise to achieve high-fidelity gates as it is not limited by photon scattering [2]. Moreover, microwave elements are potentially easier to control and integrate into the ion trap than their laser-based counterparts. Here we present recent results following the near-field gradient approach [3] using a single microwave element [4] for state manipulation and control of the qubits. At first, ion trapping and microwave control of the hyperfine states on a laser cooled 9Be+ ion trapped 70 μm above a single-layer ion trap is presented. In such a trap we demonstrate motional-sideband ground state cooling, low motional heating rates and fidelity gates above 98% on a field-independent qubit transition. In a second part, the operation of a multilayer ion trap with three-dimensional microwave circuitry is described [5]. This trap has been fabricated based on a novel multilayer-based ion trap technology capable of embedding thick elements composed of several metal-dielectric layers [6]. We finally discuss possible new routes to realize state-of-the-art microstructured ion trap devices with integrated microwave circuitry.

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A. Bautista-Salvador et al., *ArXiv:181201829 Quant-Ph* (2018).

1.15 (Sensing) Engineering a source of Bell-entangled atoms

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The CEBBEC project aims at creating, detecting and exploiting Einstein-Podolsky-Rosen and Bell entanglement in atomic Bose-Einstein condensates (BEC). In a first part of the project, the Vienna group is developing a source of momentum-entangled twin atoms. Twin atoms are the atomic analog of the twin photons generated through parametric down-conversion, which are widely used in optical quantum technologies.
Twin atoms are emitted from a source BEC through an atomic four-wave mixing process, where the non-linearity is provided by the interatomic interactions. The geometry of the experiment sets the phase-matching conditions and therefore defines the signal and idler modes populated by the atoms. Over the past years it was experimentally demonstrated that twin atoms share some properties with twin photons: their relative intensity is squeezed and they exhibit momentum correlations [1]. We report here the emission of twin atom beams in a double-well trapping potential, a geometry where the twin beams are expected to be Bell-entangled [2].

We trap and manipulate the atoms with an atom chip, which consists of a surface with micro-fabricated structures generating magnetic fields. It permits implementing fast and accurate deformations of the magnetic potential. With the atom chip we perform high-fidelity quantum optimal control of the BEC's motional state [3]. We thus initialize the twin-atom source. We then characterize the correlation properties of the emitted twin atoms.

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1.16 (Sensing) The H2020 European Project CLONETS: An optical-fibre network for clock services in Europe.

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CLONETS (Clock Network Services) is a European Union funded project, which strives for the creation of a sustainable, pan-European optical fibre-based network providing high-performance time and frequency (T&F) services to research infrastructures as well as support to a wide range of industrial and societal applications. The project is motivated by recent progress in T&F metrology and the increasing number of applications, which either are in demand for more accurate and stable T&F reference signals than are currently available through satellite techniques, or cannot rely on broadcasted signals due to, for example, security concerns or reception issues. Additionally, the development of high performance T&F dissemination techniques using optical fibre networks has led to a rich range of possibilities for optically connecting national metrology institutes (NMIs) and laboratories in and across Europe.
Optical fibre links have shown excellent performances in transmitting T&F signals on the continental scale. Consequently, they have not only become essential for comparing remote state-of-the-art optical clocks, but also a promising alternative for distributing ultra-stable and accurate T&F reference signals with applications in a wide range of fields including quantum metrology, tests of fundamental physics, atomic and molecular high-resolution spectroscopy, radio astronomy and geodesy. Such high-performance applications often rely on the availability of fibre links between dedicated sites. While some links have been established and are being operated in Europe, they are not yet interconnected.

CLONETS brings together expertise from NMIs, research laboratories, research and education networks (NRENs) and innovative high-technology small and medium enterprises (SMEs) towards creating a unified and sustainable vision of a European optical fibre network providing clock services. We are particularly interested in making contact with potential users of the CLONETS services, and potential partners in developing an optical-fibre infrastructure for specific research applications. In this presentation, we will report on the most recent progress of the project.
Presented on behalf of the CLONETS project participants.

1.17 (Sensing) Electrically readout single electron spin qubit in diamond

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The outstanding properties of the negatively charged Nitrogen-vacancy (NV-) color centre in diamond make it a promising room temperature qubit, with numerous applications in the fields of quantum sensing and quantum information science. These applications all require the readout of single NV spin state.
Recently, the photoelectric detection of NV magnetic resonances (PDMR) - based on the detection of the photocurrent induced by the two-photon ionization of NV- - has been developed as an alternative to the classical optical readout (ODMR), with advantages in terms of compactness, spatial resolution and integration with device platform [1]. The photoelectric readout was initially demonstrated on large NV- ensembles [1] and then on a few NV- centres [2].

We present here the photoelectric readout of a single NV- centre electron spin [3], required to enable implementation of the PDMR method for quantum information science and nanoscale quantum sensing. We show that under similar conditions PDMR can lead to detection rates more than two orders of magnitude higher than optical detection, since contrary to the photoluminescence rate the photocurrent does not saturate under high laser power. We demonstrate the photoelectric readout of a coherently driven single NV- spin (detection of Rabi oscillations). In these pulsed measurements, we could obtain photoelectric contrasts comparable or better than optical contrasts observed under identical experimental conditions. The photoelectric readout of the spin state was achieved by a method developed in our previous work [2], in which the trains of laser and microwave pulse sequences are encoded into a low-frequency TTL envelope provided as a reference to a lock-in amplifier used for photocurrent detection. The presented method can be used on shallow as well as deeper NV- centres. We discuss the downscaling of the device to operate in ballistic regime, with single electron counting that would enable readout at the quantum limits.

The results presented here constitute a critical step towards the development of electrically readout single electron diamond quantum chips, integrated with electronics.

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1.18 (Communication) Superconducting detectors for quantum communication

Gabriele Bulgarini [1]

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Single photon detectors play a crucial role in quantum communication technology. In the last years, superconducting nanowire single-photon detectors (SNSPDs) are emerging as the new standard in single photon detection because they provide unparalleled performance. The device operation is based on the transition of a metallic nanowire from the superconductive to the resistive state upon the absorption of a single photon. In this presentation, I will present the latest advances on NbTiN superconducting single-photon detectors operated in closed-cycle cryogenic systems. Key performance parameters are detection efficiency, timing jitter, dark count rate, and the saturation count rate. In particular, I will explain how the detection efficiency of such superconducting detectors can be tailored to obtain near unity efficiency from the visible to the telecom range and how timing resolution as low as 10 ps FWHM has been demonstrated by employing cryogenic amplification electronics to readout the detection pulses. Although such photon detection systems find naturally application in quantum cryptography, quantum communication, and optical quantum computing, it is important to note that many applications are foreseen outside the pure quantum technology domain. Potential applications where sensitivity to extremely low light intensity is required are laser ranging, semiconductor defect analysis, and medical imaging.

1.19 (Simulation) Quantum information scrambling in cQED systems

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In our theoretical work we investigate the dynamics following a global parameter quench for the ensemble of atoms confined in the cQED system. In recent experimental realizations it was shown that it is possible to engineer interactions between distant atoms with almost arbitrary strength and achieve regimes of fast scrambling. The fast scrambling conjecture — inspired by studies of the black-hole information problem — predicts a lower bound on the time for information to spread from one to all degrees of freedom of an N-body quantum system, scaling as $t_* \propto \ln N$. It is of practical importance, because a fast scrambler is an efficient quantum encoder in the sense of being able to quickly entangle quantum information across many physical quantum bits. It is conceptually important because a signature of the quantum physics of black holes is now believed to be precisely fast scrambling. In our work we particularly focus on the growth of entanglement and spreading of correlations in regimes close to fast scrambling.

1.20 (BSCC) Integration and characterization of light-emitting diodes based on layered heterostructures on photonic cavities

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[3] University of Ioannina – Greece

Layered materials and their heterostructures provide a promising and exciting technological platform for exploring new applications in photonics and electronics, such as tunneling junctions [1], photodetectors [2] and light-emitting diodes (LEDs) [3]. In particular, LEDs based on layered materials exploit the bright direct bandgap of semiconducting monolayer transition metal dichalcogenides (1L-TMDs) [4]. A key parameter to define the performances of LEDs is the external quantum efficiency (EQE), *i.e.* the ratio between emitted photons and injected electrons. Thus far, the EQE in LEDs based on layered heterostructures reached values around _˜ 0.2% [5]. Here, we fabricate LEDs via vertically-stacking single-layer graphene, used as a transparent electrode for charge injection, a few-layer of insulating hexagonal boron nitride, used as a tunnel barrier, and a 1L-TMDs (MoS2, WS2, WSe2) for light emission. We demonstrate that a chemical treatment using the superacid bis(trifluoromethane)sulfonimide (TFSI) enhances by more than four times the EQE in layered heterostructures LEDs, reaching values up to 1%. Starting from this result, we will present simulations and modelling of a possible route, based on the integration of LEDs with photonic cavities, for further enhancement of the EQE up to 40%, a value that is 2.5 higher compared to the record EQE achieved with Pervoskite-based LEDs [6]. Our devices open a path to highly efficient LEDs.

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1.21 (Computation) Practical designs for permutation symmetric problem Hamiltonians on hypercubes

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I will present a method to experimentally realize large-scale permutation-symmetric Hamiltonians for continuous-time quantum protocols such as quantum walk and adiabatic quantum computation. In particular, the method can be used to perform an encoded continuous-time quantum search on a hypercube graph with 2^n vertices encoded into 2n qubits. We provide details for a realistically achievable implementation in Rydberg atomic systems. Although the method is perturbative, the realization is always achieved at second order in perturbation theory, regardless of the size of the mapped system. This highly efficient mapping provides a natural set of problems which are tractable both numerically and analytically, thereby providing a powerful tool for benchmarking quantum hardware and a testbed for experimentally investigating the physics of continuous-time quantum protocols.

The most well known permutation symmetric problem is Grovers search, which has been proven to be able to gain an optimal $\sqrt{N}$ (N=2^n) speedup in both continuous time quantum walks and adiabatic quantum protocols. There are however many other permutation symmetric problems which have been used to demonstrate advantages of adiabatic quantum computing, for instance the spike problems introduced in [Farhi, Goldstone and Guttmann arXiv:quant-ph/0201031] which show an exponential speedup of AQC over simulated annealing. In the past permutation symmetric problems have always been considered a tool for theoretical proofs, but not something which could be practically implemented. Our work provides such a practical implementation.

1.22 (Simulation) Investigating many-body quantum phenomena with dipolar gases of erbium atoms.

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For more than two decades, ultracold quantum gases, made of bosonic or fermionic particles, have constituted a fruitful platform, opening both new frontiers in the fundamental understanding of modern quantum physics and new perspectives for quantum simulation on large yet highly controllable particle assemblies. Dipolar interactions, by being long-range and anisotropic, deeply enrich the prospects opened by ultracold quantum gases, so that their study has become, within the last years, one of the most successful and competitive areas within the quantum gases research community.
In our group, we investigate quantum gases of atomic erbium, which is among the most magnetic species of the periodic table. In these gases, we have revealed new regimes for the many-body physics, both in bosonic and in fermionic assemblies. In bosonic assemblies, we have observed exotic states of matter, quantum-stabilized droplets and roton excitations. These states, whose properties intrinsically relates to the many-body correlated behavior, connect to new kinds of superfluid states, and eventually to a supersolid. In fermionic assemblies, we have created controlled mixtures of different spin flavors and been able to tune their interactions. This paves the way to future studies of their many-body behavior, both in lattice geometries and in bulk. This yet unexplored field is expected to be marked by huge correlations. In my poster, I will review those work and our future investigation directions.

1.23 (Sensing) Compact Magnetometry Device based on Nitrogen Vacancy Centers in Diamond

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We realize a practical device design for nitrogen vacancy (NV) magnetometry to be performed outside of a laboratory setting. Highly sensitive, bio-compatible, room-temperature magnetometry devices have many potential applications in medicine and biology, which has motivated the extensive development of magnetometry techniques using NV centers in diamond. The use of such techniques for these applications requires that the sensor should be safely and conveniently accessible to being placed near the target measurement area. We have designed a portable setup with efficient NV pumping and fluorescence detection, which can be fully contained inside of a small, handheld box. With this device, we achieved a 90 $nT/\sqrt{Hz}$ sensitivity over a bandwidth of 1kHz using a diamond with native NV concentration. These results are limited primarily by pump leakage onto the photodetector and technical noise from the laser. A sensitivity in the 1-10 $nT/\sqrt{Hz}$ range is possible with mirror coating improvements and technical noise cancellation. With additional improvement in NV concentration and isotopic purification, sensitivity in the $pT/\sqrt{Hz}$ range can be achieved in a user-friendly device, allowing for magnetocardiography and for measurement of radial nerve activity.

1.24 (BSCC) Heat Transport and Thermo-power in a Single-Quantum-Dot Transistor

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We report on the thermo-electricity and the heat transport in a tunnel-contacted and gate-tunable individual single-quantum dot junction, fabricated using the electromigration technique. A pair of hybrid Josephson junctions inserted in the vicinity of the junction enable us to raise and/or monitor the electronic temperature of one of the two leads, the other one being well thermalized to the bath. Using this set-up, we could study the heat dissipation in the quantum-dot junction as a function of both the gate potential and the bias. The data highlights the gate-sensitivity of the thermal conductance through the quantum dot.

In the Kondo regime, we report the first measurement of the Seebeck coefficient. This fundamental thermoelectric parameter is obtained by directly monitoring the magnitude of the voltage induced in response to a temperature difference across the junction, while keeping a zero net tunneling current through the device. Striking sign changes of the Seebeck coefficient are induced by varying the temperature, depending on the spin configuration in the quantum dot. The comparison with numerical renormalization group (NRG) calculations demonstrates that the tunneling density of states is generically asymmetric around the Fermi level in the leads, both in the cotunneling and Kondo regimes.

1.25 (Communication) Development of a new platform for quantum photonics applications

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Very recently, the interest for quantum technologies by the scientific community and industry has strongly increased. Different types of implementations have been proposed as a practical implementation for a quantum bit. Our interest lies in using single photons and single spins in solid state host matrices such as diamond (nanodiamonds or membranes). Integration of nanosources of light is currently a major bottleneck preventing the realisation of all-photonic chips for quantum technologies and nanophotonics applications. Nanophotonics and integrated optics are vast growing fields with huge market potentials in particular for quantum technologies. Ideally, one needs optical circuitry, on-chip photodetection and on-chip generation of quantum states of light (single photons, entangled photons...). Our recent work on a new platform for quantum photonics using integrated optics can offer an easier and robust way to create fixed and compact quantum circuits that can be on chip and scalable. In this context, the coupling between waveguides and single photon emitters is critical. The goal of our research is to efficiently couple single photon emitters with a new platform made of optical glass waveguides. To achieve this goal, several paths are undertaken such as the use of dielectric and plasmonic structuration in order to increase the light interaction with the waveguide or to develop fabrication techniques to insert the emitters directly inside the guide (for nanodiamonds). We will show what is our current state of the art for placing single emitters at the right place on our optical waveguides made of ion-exchange in glass and in particular what can be done to improve our first promising results in order to get near unity coupling between the optical bus and single photon emitters. We will present some promising results using negatively charged silicon-vacancy (SiV-) centers in diamonds as they have emerged as a very promising candidate for quantum emitters due to their narrow line emission.

1.26 (Sensing) Advances in correlation plenoptic imaging

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Plenoptic imaging is an intriguing optical modality enabling refocusing, depth of field extension and single-shot 3D imaging. As such, it is quite promising in many fields of applications, from microscopy, to industrial inspection, and space imaging. Standard plenoptic devices employ a microlens array to retrieve, in the same sensor, both the image of the scene and the propagation direction of light; as a consequence, the image resolution is highly compromised and can never be diffraction-limited.
We address this issue by exploiting the quantum (or quantum-like) spatio-temporal correlations of light, so as to retrieve the spatial and directional information on two separate sensors. This novel approach, named correlation plenoptic imaging (CPI), enables to perform plenoptic imaging with diffraction-limited image resolution, as well as to achieve a surprising relief of the typical trade-off between resolution and depth of filed. Both theory, simulation, and experiments will be presented. In particular, we will show that CPI is enabled by both chaotic sources and entangled photon pairs/beams, such as those produced by spontaneous parametric down conversion (SPDC).

We are currently employing chaotic light-based CPI to achieve scan-less 3D microscopy of biomedical samples/phantoms. The scheme has been designed so as to enable imaging with turbulence mitigation, as required in both biomedical microscopy and space imaging. Both the working principle and preliminary experimental results will be presented.

A novel CPI scheme based on entangled beams from SPDC will also be presented, together with its peculiar capability of minimizing the noise; this is a particularly relevant result in view of employing CPI for imaging low absorbing samples typical of biomedicine.

Future perspectives will be offered, mostly dedicated to maximizing the speed of CPI in view of its widespread applications.

1.27 (Computation) Single shot high fidelity QND qubit readout using a transmon molecule in a 3D cavity

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Using the transverse dispersive coupling between a qubit and a microwave cavity is the most common read-out technique in circuit-QED. However, despite important progresses, implementing a fast high fidelity readout remains a major challenge. Indeed, inferring the qubit state is limited by the trade-off between speed and accuracy due to Purcell effect and unwanted transitions induced by readout photons in the cavity. To overcome this, we introduce a transmon molecule circuit design coupled to a 3D-cavity [1,2]. This system presents one transmon qubit with a large direct cross-Kerr coupling to a weakly anharmonic mode, called polariton mode. This polariton mode results from the hybridization between the microwave cavity and the second mode of the transmon molecule circuit and is used to readout the qubit state. Direct cross-Kerr coupling is a key point to our readout scheme since such a coupling is immune to Purcell effect. We will present qubit readout performance, without quantum-limited amplification, with fidelity as high as 97.2% in 500ns thanks to polariton non-linearity. We will also present, in the linear regime, with quantum-limited amplifier, fidelity as high as 94.7% in 50ns and quantum trajectories with high time resolution where the qubit state is measured quantum non-destructively 99% of the time.

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1.28 (Computation) Cryogenic CMOS electronics as building blocks for scalable quantum computers

Carsten Degenhardt [1], Anton Artanov [1], Volker Christ [1], Lotte Geck [1], Christian Grewing [1], Andre Kruth [1], Daniel Liebau [1], Pavithra Muralidharan [1], Dennis Nielinger [1], Petra Schubert [1], Patrick Vliex [1], Andre Zambanini [1], Stefan Van Waasen [1,2]

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The Central Institute for Electronic Systems at Forschungszentrum Jülich develops, designs and tests scalable solutions for the control and readout of qubits to be used in future quantum computers. The focus lies on highly integrated system-on-chip (SoC) solutions leveraging state-of-the-art commercial semiconductor technologies.
A test chip was designed and layouted in a commercial 65nm CMOS process. The chip features a DC-digital-to-analog converter (DC-DAC) that generates tuning voltages, e.g. for spin qubits, in the range of 0 V to +1 V. The integrated pulse DAC, running at 250 MHz, generates pulses with ± 4 mV amplitude as gate sequences for operating the qubit.

In this presentation, we will describe the chip architecture in detail, show corresponding simulation results and measured chip performance.

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1.29 (Communication) Metrology for Quantum Communication: results and perspectives in the context of the EURAMET European Metrology Network for Quantum Technologies

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The European Metrology Network on Quantum Technologies (EMN-Q, a EURAMET body) would directly impact companies by developing cutting edge quantum research activities in the context of the pillars of the EC Quantum Flagship, as well as developing the necessary metrological infrastructure for the characterisation of the quantum devices and for their certification. Furthermore, the EMN-Q measurement expertise will coordinate fundamental contributions to the standardisation process of these device.
In particular, regarding Quantum Key Distribution (QKD) the EMN-Q answers to the needs concerning in the electronic communications sector. Progress in quantum computing and crypto-analysis will render some forms of current encryption insecure. QKD will be used to secure future communications. It is clear that the European citizen should have greater confidence in Quantum Cryptography if systems have been tested and certified by independent bodies.
Although QKD can be proven unconditionally secure in theory, in practice any deviations of the real system from the idealised model could introduce vulnerabilities. The security of real systems requires physical characterisation. Measurements are therefore required to characterise QKD components and modules, their vulnerabilities and counter-measures to them.
Specifically, European Metrology institutes have already carried on activities for assessing QKD and its components, so that we better understand how QKD components, counter-measures to attacks, and new types of QKD which are in principle more robust to attacks, perform in an adversarial environment. A transformation of these results into a reliable, efficient and market-oriented metrological approach is necessary for maintaining the leading role of Europe in the quantum communication field. QKD exploiting satellites appears to be the only viable solution for achieving QKD worldwide, thus a metrological infrastructure able to provide appropriate characterisation of optical components for free-space QKD is absolute necessary. In a dedicated (EURAMET) project (EMPIR 14IND05 MIQC2) the realisation of such an infrastructure has already been started.

1.30 (Sensing) A novel measurement paradigm: Genetic Quantum Measurements

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In quantum mechanics measurements, following the Von Neumann scheme,are described as a sequence composed of state preparation, strong interaction (described by a unitary operator), and state detection (typically described with the projective measurements formalism). Genetic Quantum Measurements (GQMs) represent a paradigm shift, since they use genetic-like approach to significantly surpass the performances of the conventional (projector-based) quantum measurement techniques. Indeed, GQMs, after the usual initial state preparation, take advantage of a repeated sequence of interaction and recombination leading to quantum interferences (here taking the role of the crossover in genetic processes) and selective measurements (corresponding to the genetic selection pressure). The quantum mechanical Superposition Principle, at the heart of the quantum parallelism advantage exploited in several of the forthcoming quantum technologies such as, e.g., quantum computers, plays the role of mutation, necessary to explore different evolution paths. Thanks to the quantum parallelism feature, in the GQM approach, all the possible "evolution trajectories" are explored at the same time.
GQMs concept,in analogy with sequential measurements [1,2], exploits a sequence of interactions, but also takes advantage of a continuous protection of the quantum as in the case of protective measurements [3,4]. GQMs approach considers a finite amount of interaction-selection stages and investigates any interaction intensity, from weak to strong, in order to optimize the trade-off between single quantum system survival and uncertainty reduction. In some sense, it can be considered as a practical and (astonishingly) useful version of the ideal concept of protective measurement.

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1.31 (Simulation) Qubit and quantum gate memristive simulator

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Quantum simulators can be used for the development and evaluation of new quantum algorithms. Software-based quantum simulators, executed on classical computers, suffer from exponential slowdown as the number of qubits is increased. Here we present the fabrication and use of memristor circuits to represent qubit states. Qubit states are mapped to a 3D memristance space spanned by three memristors, and the method of mapping Bloch sphere surface points to the memristance space is presented. General rotations of the qubit state vector in the Bloch sphere, that represent actions of one-qubit quantum gates are mapped to paths in the 3D memristance space. We define the correspondence between the action of quantum gates during quantum computation with the variations of the three memristor input voltages that generate these paths. The action of the two-qubit Controlled-Not (CNOT) quantum gate is represented by input voltage variations of two three-memristor groups, which span a six-dimensional memristance space. We also simulate the action of a Hadamard quantum gate followed by the action of a CNOT gate, a quantum circuit that generates entangled two-qubit states. The memristors we use are fabricated using Metal-Insulator-Semiconductor structures (MIS). More specifically, the memristive material is made of silicon nitride while Cu and heavily doped Silicon are acting as active and inert electrodes respectively. LPCVD silicon nitride is a well-known material in microelectronics used already in commercial memory devices. Both conductivity types of Si n++ and p++ have been tested. The devices have been characterized in terms of static I-V, resistance variability, impedance spectroscopy and retention measurements. Room temperature I-V measurements suggest that a trap-assisted-tunneling and space charge limited conduction (SCLC) are dominating through the nitride layer. The analog behavior of our memristive devices is evaluated under different frequency variable signal. By representing qubit states with three-memristor circuits and the action of quantum gates with memristor input voltage variations, we developed an analog quantum simulator that can be used for the development of new quantum algorithms involving a large number of qubits.

1.32 (BSCC) Bayesian estimation for quantum sensing in the absence of single-shot detection

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Sensors based on individual quantum systems combine high sensitivity and spatial resolution in measuring physical quantities [1]. The performance of quantum sensors can be enhanced by using quantum information protocols such as quantum error correction and quantum phase estimation. For instance, quantum phase estimation algorithms have proven helpful in the context of high dynamic-range sensing [2]. These protocols have
relied on the availability of single-shot detection, which delivers a binary outcome. However, sometimes only an averaged readout is available, as for the case of room-temperature sensing with the electron spin associated with a nitrogen-vacancy center in diamond [3]. Here, we theoretically investigate the application of the quantum phase estimation algorithm for high dynamic-range magnetometry, in the case where single-shot readout is not available. We show that, even in this case, Bayesian estimation provides a natural way to use the available information in an efficient way. We apply Bayesian analysis to achieve an optimized sensing protocol for estimating a constant magnetic field with a single electron spin associated to a nitrogen-vacancy center at room temperature and show that this protocol improves over a factor of 3 in sensitivity over the previous work [4]. Moreover, we show that an extra enhancement can be achieved by considering the timing information in the detector clicks.

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1.33 (Computation) Tetrapartite entanglement measures of W-Class state with uniform acceleration

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In this paper we calculate entanglement measures, negativity (1-3 tangle and 1-1 tangle) and von Neumann entropy. We also make an analysis between the whole entanglement measures (π4 and Π4), for the tetrapartite W-Class system in a noninertial frame at uniform acceleration by using Rindler transformation for a fermionic field. The entanglement properties are compared among the different cases from one accelerated qubit and others stationary to four accelerated qubits and no one stationary. The results show that there is not any loss of entanglement for the complete system. in some cases the negativity when qubits archive r = 1, but when the 1 - 1 tangle is measured there is a loss of entanglement in r $>$ 0.472473.

1.34 (Simulation) Barrier induced oscillations and decay of the current in a one-dimensional Bose gas

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We study the dynamics of the current in a one-dimensional Bose gas with periodic boundary conditions, in the presence of a barrier. The system is quenched from an equilibrium state to a circulating state and, because of the barrier the current evolves. We use analytical and numerical approaches to compute the dynamics, both in the weakly interacting (mean field) and in the strongly interacting (Tonks-Girardeau) limits, at zero and finite temperature. We evidence different qualitative behaviours depending on the interaction, barrier strength and temperature regimes. In particular the weak interactions and low temperature regime gives rise to an effective "dual" Josephson dynamics between angular momentum states. At finite temperature we observe a damping of the current which we relate to phase-slips involving soliton excitations. This work is relevant to understand transport properties in ring shaped cold-atom traps a key element of atomtronics.

1.35 (BSCC) Rydberg-Regulated Interactions between Trapped Ions and Ultracold Atoms

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Trapped ions are among the leading quantum computer platforms since they currently feature some of the highest fidelity quantum logic gates [1]. However, further improvement is required for attaining a both scalable and fault-tolerant quantum system. Inasmuch phonons mediate quantum logic operations within ion crystals, residual motion and heating due to coupling to stray electric fields reduces the fidelity of these operations as well as the overall coherence. In contrast to elaborated trapped-ion quantum computers which rely on laser cooling, we attack this problem by employing buffer gas atoms of sufficiently low temperatures as a coolant. Our hybrid system of trapped Yb+ ions immersed in a cloud of ultracold Li atoms lets us forge a gateway to enter and uphold the quantum regime [2]. Vital for our idea to bear fruit is the ability to tune the atom-ion interactions with external fields. We report on a novel way of doing so by laser coupling to Rydberg states [3] – allowing to tune the atoms' polarizability, and thus to engineer the charge-induced atom-ion interaction. The rate of observed inelastic collisions, which manifest themselves as charge transfer between the Rydberg atoms and ions, exceeds that of Langevin collisions for ground state atoms by almost three orders of magnitude. To describe the exhibited shape of the ion loss spectra, we need to include the ion-induced Stark shift on the Rydberg atoms. Furthermore, we demonstrate Rydberg excitation on a dipole-forbidden transition with the aid of the electric field of a single trapped ion. Adding dynamic Rydberg dressing may allow for: (i) the creation of spin-spin interactions between atoms and ions, enabling atom-ion quantum gates [4], and eventually an atom-ion quantum interface merging the unparalleled fidelity of the ionic system with the intrinsic scalability of the atomic system; (ii) the study of solid-state quantum physics [5]; and (iii) the elimination of collisional heating due to ionic micromotion in atom-ion hybrids [6].

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1.36 (Computation) CMOS hole spin qubit readout by gate reflectometry

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The last period has witnessed many breakthroughs in the field of silicon-based spin qubits. However, single holes spins in Si remain a barely explored hosting platform if compared to electron spin in quantum dots.
Our team has shown that holes in Si transistors can be employed to encode quantum information. Hole spins carry major advantages with respect to their electron counterparts; for instance, we expect long coherence times due to the absence of contact hyperfine interaction; also, strong spin-orbit coupling enables fast coherent spin rotations using a radio-frequency electric field.
In favour of a potential scalability of qubit devices, gate radio-frequency reflectometry has been proposed as a competitive technique for spin readout as it involves a minimal hardware overhead at the qubit layer. In this poster, we show the implementation of gate reflectometry on a fully functional spin qubit device consisting of a p-type double-gate transistor made using CMOS industry-standard silicon technology.

1.37 (BSCC) Charger-mediated energy transfer for quantum batteries: an open system approach

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The energy charging of a quantum battery is analyzed in an open quantum setting, where the interaction between the battery element and the external power source is mediated by an ancilla system (the quantum charger) that acts as a controllable switch. Different implementations are analyzed putting emphasis on the interplay between coherent energy pumping mechanisms and thermalization.
Specifically, we have studied three models: one in which both the charger A and the quantum battery B are described by harmonic oscillators, one in which both A and B are qubits and, finally, one in which A is a harmonic oscillator and B is a qubit. In all cases, the charger A interacts with an external energy supply E, and acts as mediator between E and B. Initially both A and B are in the ground state with zero energy, and energy is dynamically injected into the system thanks to the presence of the external sources E, either via the presence of a thermal bath at temperature T and via a coherent driving field of amplitude F. Particular attention has been devoted to the maximum extractable work from B, i.e. the so-called ergotropy.

Our main findings can be summarized as following.

(i) The case of two harmonic oscillators is profoundly different from the other two cases. Because of the linearity of the system, in the case of two harmonic oscillators there is no interplay between the coherent and incoherent energy supplies. In particular, in the coherent protocol ($F > 0$, $T = 0$), ergotropy and energy coincide. This happens because A and B remain uncorrelated during the system's evolution.

(ii) In the case of the thermal protocol ($F = 0$, $T > 0$), the ergotropy is always zero. This holds true for all models.

(iii) In the case of two qubits in the mixed regime ($F > 0$, $T > 0$)

(while typically non-zero temperature tends to reduce the ergotropy) there are special settings for which finite temperature is beneficial for the ergotropy. This is a consequence of the nonlinear character of this model, which leads to a non-trivial interplay among coherent and incoherent channels.
(iv) In the hybrid model, the time at which energy and ergotropy are maximal decreases mono-

tonically with the driving field F. This peculiarity stems from the structure of the Hilbert space of the hybrid model (see "Physical Review B 98.20 (2018): 205423" for a comparison in a closed, i.e. Hamiltonian, setting).

1.38 (Computation) Efficient Quantum Compiling for Quantum Chemistry Simulation on IBM Q

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Current quantum processors are noisy, have limited coherence and imperfect gate implementations. On such hardware (named Noisy Intermediate-Scale Quantum or simply NISQ), only algorithms that are shorter than the overall coherence time can be implemented and executed successfully. One promising candidate that provides such short-depth algorithms is the variational quantum eigensolver (VQE) method that, for instance, allows the efficient calculation of the ground state wavefunction of simple molecular systems.
Since 2016, IBM offers cloud-based access to its experimental quantum computing platform, denoted as IBM Q Experience [1]. Quantum circuits can be designed and executed by means of the Qiskit Python SDK. Qiskit has two main elements, namely Qiskit Terra (functional roots) and Qiskit Aqua (algorithms); Qiskit Terra provides a quite large set of quantum gates for the user's convenience.

Quantum compiling means fast, device-aware implementation of quantum algorithms. With respect to IBM Q devices, there are device-specific physical constraints that prevent from placing CNOT gates wherever they are needed. Qiskit Terra comes with a default compiler, based on a randomized algorithm. In the following, "compiling" always implies "on IBM Q devices."

In a recent work [2], we illustrated an effective strategy for compiling low-depth quantum circuits that generate GHZ states. In this work, we present further strategies for compiling relevant (i.e., recurrent) quantum circuit patterns. In particular, such patterns appear in quantum circuits that are used to compute the ground state properties of molecular systems using the VQE algorithm together with a wavefunction ansatz like the Coupled-Cluster (CC) expansion. Compared to the circuits produced by Qiskit Terra's default compiler (v0.6.1), our ones have lower depth. We are collecting our compiling strategies into a Python library that can be used an appendix to Qiskit Terra.
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1.39 (Computation) Relaxation and decoherence time estimations of the hybrid qubit in Silicon quantum dots

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We study theoretically the phonon-induced relaxation and decoherence processes in the hybrid qubit defined in silicon quantum dots. The hybrid qubit is realized starting from an electrostatically defined double quantum dot where three electrons are confined and manipulated through only electrical potentials. The hybrid qubit behaves as a charge qubit when the interdot energy detuning is close to zero and as spin qubit for large detuning values. In quantum computation applications the study of qubit realized in silicon deserves indeed large interest due to its advantages in terms of fabrication, control, manipulation and potential for scaling, in addition to the compatibility with the existing CMOS technology. By employing a three-level effective model for the qubit and describing the environment bath as a series of harmonic oscillators in the thermal equilibrium states, we extract the relaxation and coherence times as a function of the bath spectral density and of the bath temperature using the Bloch-Redfiled theory. For Si quantum dots, the energy dispersion is strongly affected by the physics of valleys, i.e. the minima of the conduction band, so we also included the contribution of the valley excitations in our analysis. Our results offer fundamental information on the system decoherence properties when the unavoidable interaction with the environment is included and temperature effects are considered.

1.40 (Sensing) Engineering of nitrogen-vacancy centers in diamond for quantum sensing

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The negatively charged nitrogen-vacancy center in diamond (NV– center) is an appealing quantum system for sensing and information processing purposes, due to its unique photophysical properties combined with ease of access and manipulation in a solid state system denoted by high transparency and structural stability. This contribution will provide an overview of the most recent results obtained on the fabrication and exploitation of NV– centers at the National Institute of Nuclear Physics (INFN), in collaboration with the University of Torino and the Italian National Institute of Metrology Research (INRiM), as well with other partner institutions.

The latest activities on the fabrication of NV– centers in bulk and nano-crystalline diamond will be presented, including:
- the exploitation of innovative schemes for the electrical control of nitrogen-vacancy centers in bulk single-crystal diamond by means of integrated graphitic electrodes [1,2];
- the definition of an optimal protocol for the fabrication of NV– centers in nanodiamonds (NDs), both at the high density ensemble and at the single-photon emitter level [3], by means of proton irradiation and subsequent thermal and chemical processing.

The ongoing research on the utilization of NV– centers for quantum sensing and imaging purposes will also be discussed, with a specific focus on:
- the employment of ensembles of NV– centers for the quantum-sensing and high-resolution mapping of local electrical fields in diamond-based devices through the measurement of the Stark-shifted optically-detected magnetic resonances (ODMR) of the defects [2];
- the assessment of the effects of NDs internalization in networks of cultured hippocampal neurons for optical bio-labelling, drug-delivery agents and field sensing purposes [4].

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1.41 (Communication) Developments in the first Hungarian free-space QKD experiment

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In November 2017, Hungary has started a 4-year-long national quantum technology flagship project with a budget around 10 million euro. The national consortium has 7 members from academia, research institutes as well as companies including Ericsson Hungary, Nokia Bell Labs and BHE Bonn Hungary Ltd (a Hungarian aerospace company). The Hungarian flagship project has a dedicated track on secure quantum communications. In the past years, we built the first Hungarian fiber-based Continuous Variable Quantum Key Distribution (CV QKD) device. Building on our experience, one of the current tasks is focusing on entanglement-based free-space quantum key distribution with a potential application in the satellite domain. We started to build an experiment which will enable us to gain new competences while sharing secret keys over free space channel.

Meanwhile, we started to analyze the atmospheric properties of free-space channels. We have developed a mathematical model for quantum-based satellite communication. Our model is based on classical Gaussian beam propagation and it focuses on losses. It takes into account several factors: the atmospheric losses due to molecular and aerosol extinction, technological limitations such as detector efficiency and photon production efficiency and it analyzes the effect of pointing error and beam spreading given a certain detector mirror size. We compared predictions of the model with experimental results, and a computer program based on the model is now available.

On the experimental side, we have created and tested an entangled photon pair source at 850 nm wavelength based on a thin BBO crystal plate, using Type I phase matching condition. We integrated this photon source into a setup to test transmission of photon pairs over short distances in free space and successfully detected coincidences.

1.42 (Sensing) Atom trapping with dressed states for rotation sensing

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Dressing atoms with radio-frequency and microwave radiation opens up new possibilities for ultra-cold atoms and a BEC in new types of trap and in new topologies involving wave-guides [1,2]. This is because of the flexibility inherent in the vector coupling of a magnetic dipole moment to electromagnetic fields which can be varied in time, frequency, orientation and space. This may in turn result in quantum technology applications to sensing (with ring traps and gyroscopes [3,4]), metrology, interferometry and atomtronics as well as applications to atomic lattice physics [5,6].

Here we give two recently developed applications of dressed atom theory which are relevant to experiments and quantum technology: the first shows how "double-dressing" with radio-frequency and microwave fields can be used to optimise realistic field inhomogeneities. The second application analyses the microwave spectroscopy of radio-frequency dressed states: this is relevant to experiments developing rotation sensors based on the Sagnac effect with matter-waves [7].

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1.43 (Sensing) CMOS SPAD arrays for Quantum Imaging

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Single-Photon Avalanche Diodes (SPAD) are able to detect individual photons and measure their arrival time with _~100-ps resolution.
CMOS technology allows to arrange SPADs in 2-dimensional arrays and connect them to timestamping circuits on a monolithic substrate to generate maps of photon arrival times.
CMOS SPAD arrays are applied nowadays in several photon-starved applications, mostly for biomedicine, particle physics, depth sensing and, recently, to quantum imaging.
SUPERTWIN is a H2020 FET-OPEN project that aims at achieving super-resolution microscopy using entangled photons. Within SUPERTWIN, a new CMOS SPAD array has been developed to extract the spatio-temporal correlations existing within multi-photon states.
We here present the detector, a 32x32-pixel, time-resolved single-photon image sensor capable of timestamping photons at pixel level, with a timing resolution of 200 ps within a 50-ns long observation window. The sensor achieves a record fill factor for this kind of architectures of 20%, within a pixel pitch of about 45um. The sensor is capable of acquiring images at more than 80 kfps, up to 500 kfps in case of sparse data (as in a typical experiment with entangled photon pairs generated in a non-linear crystal by spontaneous parametric down conversion). A smart on-chip mechanism skips entire frames if the number of detected photons is below a user-defined threshold (e.g., 2 photons in an experiment with 2-photon states), achieving a maximum observation rate of 800 kHz while reducing data-rate and saving processing power.
The sensor has been successfully employed in a quantum imaging experiment achieving super-resolution at the Heisenberg limit.
In the talk, we will present the sensor in details, showing its architecture, its performance in terms of efficiency in detecting photons, timestamping capabilities and noise (dark counts, cross-talk, jitter).
The sensor can be indeed considered a quantum device having 1000 channels operating in parallel. Scientists can thus replace complex setups based on scanning mechanisms with a single, USB-connected device.

1.44 (BSCC) Diagnostics and manipulation of spin-ensembles of cold rubidium atoms

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We report on the creation, observation and optimization of superposition states of cold atoms [1]. In our experiments, rubidium atoms are prepared in a magneto-optical trap and later, after switching off the trapping fields. Faraday rotation of a weak probe beam is used to characterize atomic states prepared by application of appropriate light pulses and external magnetic fields. We study the signatures of polarization and alignment of atomic spin states, and identify main factors responsible for deterioration of the atomic number and their coherence and present means for their optimization, like relaxation in the dark with the strobed probing. These results may be used for controlled preparation of cold atom samples and in situ magnetometry of static and transient fields.

In the next-generation setup, we keep atoms in a far off-resonant optical dipole trap (ODT) inside an improved magnetic shield. The ODT provides long relaxation time and large on-axis optical depth, which result in the improved sensitivity to the magnetic field. Moreover, the tight confinement of atoms enables the magnetic field probing with a spatial resolution of a few tens of micrometers.

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1.45 (Sensing) Coherent population oscillations in diamond color centers – basic properties and sensing applications

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Nitrogen-Vacancy (NV-) color centers in diamond attract much attention because of their potential for important applications in physics, biophysics and quantum technologies [1]. NV-type defect is characterized by
a nonzero electron spin (S = 1) which allows it to be optically pumped (spin polarized) by green light, probed via microwave (MW) resonance spectroscopy, and optically detected.

We present results of our research on two-field (two-frequency) microwave spectroscopy in ensemble of nitrogen-vacancy (NV–) color centers in diamond. We focus on the case where two microwave fields drive the same transition between two NV– ground state sublevels, ms = 0 ↔ ms = +1, (Fig.1a). In this case, the system's dynamics is mainly determined by the coherent population oscillations (CPO) [2]. The CPO depend on the material properties of the investigated quantum system and enable precision spectroscopy [2] and sensing applications. Specifically, the structure of the CPO resonances specifically depends on the relaxation properties of energy levels of the color centers and their interaction with the external fields. This opens possibilities for development of various sensors of magnetic and electric fields, temperature and pressure.

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1.46 (Communication) 8 GBit/s real-time quantum random number generator based on vacuum fluctuations

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Random numbers have a variety of applications for which specific quality requirements must be met. Perhaps the most demanding application is cryptography where the quality has a critical impact on security. Quantum random number generators (QRNGs) based on the measurement of quantum states promise perfectly unpredictable and private random numbers.
However, currently developed QRNGs are still facing numerous problems rendering them unsuitable in practical applications with certified randomness. A single QRNG has not fulfilled all of the following requirements:
- accounting for all noise sources as quantum side-channel information
- accounting for correlations between consecutive samples (finite detection bandwidth)
- conducting a conservative and rigorous characterization of the measurement device
- producing random numbers in real time with high speed

Here, we will present a QRNG that fulfills all the above mentioned requirements. Our system is extremely simple as it is based on homodyne measurements of the vacuum state. By accounting for quantum side-information, for temporal correlations and by performing a metrology-grade characterization of the system, we demonstrate the generation of certified random numbers in real-time with an unprecedented speed of 8 GBit/s.
To generate random numbers from homodyne measurements our device consists of a laser, a beam splitter, two photodiodes, a transimpedance amplifier, an analog-to-digital converter (ADC) and finally an FPGA. For the characterization we independently determined the noise power spectrum originating from the vacuum state by measuring the transfer function of the homodyne detection and sampling circuit by injecting coherent laser light into the signal port of the beam splitter. The real-time Toeplitz randomness extraction was implemented in the FPGA.
The generated random numbers are perfectly suited for conventional and in particular quantum key distribution (QKD). We achieved a security epsilon parameter of 10ˆ-10 which even holds after 10 years of continuous operation and for a QKD run with 10ˆ10 prepared quantum states. The achieved security and speed, combined with the possibility to implement the system on a photonic chip, renders our QRNG a promising quantum technology with widespread applications.

1.47 (Communication) Composable security of two-way continuous-variable quantum key distribution without active stmmetrization

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We present a general framework encompassing a number of continuous-variable quantum key distribution protocols, including standard one-way protocols, measurement-device-independent protocols as well as some two-way protocols, or any other continuous-variable protocol involving only a Gaussian modulation of coherent states and heterodyne detection. The main interest of this framework is that the corresponding protocols are all covariant with respect to the action of the unitary group U(n), implying that their security can be established thanks to a Gaussian de Finetti reduction. In particular, we give a composable security proof of two-way continuous-variable quantum key distribution against general attacks. We also prove that no active symmetrization procedure is required for these protocols, which would otherwise make them prohibitively costly to implement.

1.48 (BSCC) Silicon integrated photonic platforms for probabilistic sources of quantum states of light

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Integrated photonic architectures are intensively developing as they offer the prominent platforms towards the realization of compact probabilistic sources of single photons relaying on nonlinear parametric processes. The emission of a pair of photons is not directly controllable, therefore heralding schemes must be used to exploit them as single photons. Due to the mature fabrication technology and the high Chi(3) nonlinearity of Silicon, the silicon-on-insulator (SOI) platform is perhaps the best candidate for low cost and mass production of quantum devices. Due to the crystal centro-symmetry, generating quantum states of light in Silicon relays on Four Wave Mixing (FWM) scheme as a straightforward approach. However, efforts are needed to improve the state purity (need for narrow band filters) and to expand the spectral separation of signal and idler photons in order to provide with sufficient pump rejection. We resolve these limitations by exploiting the intermodal FWM in SOI rib waveguides, developed relaying on appropriate technological solutions and guiding architectures [1]. We designed, fabricated and characterized through FWM and coincidence experiments devices, which exhibit discrete band phase-matching and extremely large spectral translation between the signal (1952nm) and idler (1281 nm) when pumped at a wavelength of 1550nm. We then envision the application of intermodal FWM to on-chip heralded single photon sources.

A second line of developments addresses the generation of second-harmonic generation (SHG) or its inverse process of spontaneous parametric down-conversion (SPDC). The approach is to induce effective second-order nonlinearities in Silicon by engineering local static electric fields in the SOI rib waveguides and using the intrinsic Chi(3) nonlinearity of Silicon [2]. We develop phase-matched SOI rib waveguides with periodically patterned p-i-n junctions, where efficient SHG was measured showing conversion between wavelengths around 2400 nm and 1200 nm. The strength of the nonlinear effect depends on the applied bias, which enables the tunablility of the nonlinear process. In an SPDC scheme this can enable the generation of entangled photons at a tunable rate.

1. S. Signorini et al., *Photonics Research* 6, 805 (2018)
2. E. Timurdogan et al., *Nature Photonics* 11, 200 (2017)

1.49 (Computing) Ultrasensitive graphene bolometer

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Single-microwave-photon detection would provide a versatile tool for circuit quantum electrodynamics, which is a promising field to implement quantum computing. Currently, single-photon detectors are readily available at optical wavelengths. However, the required sensitivity of thermal detectors for single microwave photons has not been achieved yet.

To address this issue, we develop a bolometer based on a graphene Josephson junction. Due to its unusual thermal properties, graphene is a promising material to implement high-sensitivity microwave photon detection.

We couple the graphene Josephson junction to on-chip capacitors forming a temperature dependent LC oscillator. Radiation incident on the graphene modifies the resonance frequency of the oscillator, which server as our thermometer.

Our preliminary results suggest a noise equivalent power of NEP = 20 zW/ rtHz and an energy resolution in the yJ range.

1.50 (Computation) Qubit Measurement by Multichannel Driving

Joni Ikonen [1], Jan Goetz [1], Jesper Ilves [1], Aarne Keränen [1], Andras M. Gunyho [1], Matti Partanen [1], Kuan Y. Tan [1], Dibyendu Hazra [1], Leif Grönberg [2], Visa Vesterinen [1,2], Slawomir Simbierowicz [2], Juha Hassel [2], Mikko Möttönen [1]

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We theoretically propose and experimentally implement a method of measuring a qubit by driving it close to the frequency of a dispersively coupled bosonic mode [1]. The separation of the bosonic states corresponding to different qubit states begins essentially immediately at maximum rate, leading to a speedup in the measurement protocol. Also the bosonic mode can be simultaneously driven to optimize measurement speed and fidelity.We experimentally test this measurement protocol using a superconducting qubit coupled to a resonator mode. For a certain measurement time, we observe that the conventional dispersive readout yields close to {100}{} higher average measurement error than our protocol. Finally, we use an additional resonator drive to leave the resonator state to vacuum if the qubit is in the ground state during the measurement protocol. This suggests that the proposed measurement technique may become useful in unconditionally resetting the resonator to a vacuum state after the measurement pulse.
Ikonen, *et al.*, arXiv 1810.05465
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1.51 (BSCC) Spin noise spectroscopy in a metastable helium cell

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[2] Laboratoire Collisions Agregats Reactivite – Université Toulouse III - Paul Sabatier : UMR5589, Centre National de la Recherche Scientifique : UMR5589 – France

Optical spin noise spectroscopy is a powerful tool to probe spin fluctuations in various systems. Such fluctuations induce fluctuations of the Faraday rotation of a linearly polarized electromagnetic field, which can be recorded using a balanced detection [1,2]. After the pioneering work of Alexandrov and Zapasskii in 1981 [3], it needed more than 2 decades before different technical progresses allow to use it as a disturbance free probe of spin dynamics in gases [4] as well as in semi-conductors [5].
We have implemented this technique in a metastable helium cell, and a usual spin noise resonance could be detected in the vincinity of the D0, D1 and D2 resonances corresponding to the fine structure of the 3S1 to 3P transitions. But when the laser is tuned at the limit of the Doppler broadened D0 and D1 lines, another spin noise resonance is visible with unusual features such as a dependance on the light polarization direction. These resonances are studied both experimentally and theoretically.

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[3] E B Aleksandrov and V S Zapasskii, Zh. Eksp. Teor. Fiz, 81,132 (1981)
[4] S A Crooker & al, Nature 431, 49, (2004)
[5] M Oestreich & al. Phys. Rev. Lett. 95, 216603 (2005).

1.52 (BSCC) Standardization: Prepare your innovation for industry!

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1

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Despite the fact that many quantum technology areas are still basic research, first technologies are advancing on the technology readiness level scale. The aim of this presentation is to raise your awareness for standardization and to help facilitate and accelerate market uptake of your quantum technology.
The benefits for emerging technologies when considering standardization at an early stage will be explained. The basics of standardization such as rules to be applied, existing standardization organizations and the standardization process will be presented. Discussing the different types of standardization documents on different levels (national, European or worldwide) will give you an overview in order to select the appropriate exploitation for your specific innovation or issue. We will explain how national standardization bodies e. g. DIN can assist you to transfer your project findings to the industrial level.

Besides general information on standardization, the Joint Research Centre from the European Commission will give you an update on the activities currently taking place in the field of standardization and quantum technology.

1.53 (BSCC) Statistical testing of the output of a quantum random number generator

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Random numbers are an essential resource for classical, quantum and post-quantum cryptography, as well as having numerous other applications such as in computer simulation. TREL has developed a GHz-rate quantum random number generator based on spontaneous emission from a pulsed laser [1]. The randomness of the resulting terabit-sized bit streams are analysed using public domain suites of statistical tests [2, 3, 4], which are used to check the null hypothesis that the bits are random draws made independently from the uniform distribution on the two-element discrete-set {0, 1}. The test suites are used to apply statistical tests of increasing stringency, requiring bit streams of increasing length, to demonstrate that the quantum random number generator is at least as good as the best available software-based random number generators. The availability of long bit streams permits two-level tests in which the observed rates of extreme test results can be compared against expected rates. However, with such long bit streams the implementation of the tests is only made feasible by the use of high-performance computing clusters. We describe our implementation of the statistical tests for testing the output of the TREL quantum random generator, and report on our analyses of the test results.

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[3] Pierre L'Ecuyer and Richard Simard, *TestU01 A Software Library in ANSI C for Empirical Testing of Random Number Generators,* 2013. http://simul.iro.umontreal.ca/testu01/tu01.html
[4] John Walker. *Ent: A pseudo-random number sequence testing program.* http://www.fourmilab.ch/random/

1.54 (Communication) Sub-second optical storage using dynamical decoupling in an atomic frequency comb memory

Adrian Holzaepfel [1], Jean Etesse [1], Krzysztof T. Kaczmarek [1], Alexey Tiranov [1], Nicolas Gisin [1], Mikael Afzelius [1]

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Quantum memory for photons is a key quantum technology for long-distance quantum key distribution, quantum networks and the realization of a quantum internet. Rare-earth (RE) doped crystals provide solid-state quantum memories with many appealing features, such as high efficiency, multimode capacity and long storage times.
The atomic frequency comb (AFC) scheme has been used in many of the quantum storage experiments in RE crystals to date, including the recent demonstrations of spin-photon quantum correlations [1,2]. The longest storage time achieved so far in an AFC memory was around 1 ms, in a Europium-doped Y2SiO5 crystal at zero applied magnetic field [1]. This storage time as reached using a simple spin echo sequence on the nuclear spin states Eu:Y2SiO5 crystal. Longer storage times should be possible by dynamical decoupling (DD) of the spin states, but efficient DD was so far unsuccessful at zero field due to the double degenerate nuclear states.

In this poster we will present results of storage of optical pulses for up to 0.3 seconds using the AFC scheme and DD in a Eu:Y2SiO5 crystal under magnetic field. By applying a low magnetic field in a specifically chosen angle [3], we were able to split the nuclear states and increase the bare spin coherence time to about 30 ms, while keeping a simple hyperfine structure. By additionally applying a DD sequence the optical storage time reached above 300 ms. By further increasing the Rabi frequency on the spin states we expect to reach beyond 1 seconds in the near future, paving the way for long-duration storage of quantum correlations in a RE crystal.
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[2] K. Kutluer, M. Mazzera, and H. de Riedmatten, Phys. Rev. Lett. 118, 210502 (2017)
[3] E. Z. Cruzeiro, J. Etesse, A. Tiranov, P.-A. Bourdel, F. Fröwis, P. Goldner, N. Gisin, and M. Afzelius, Phys. Rev. B 97, 094416 (2018)

1.55 (Simulation) Subradiance in V-type multilevel emitters

Raphael Holzinger [1], Laurin Ostermann [1,2], Helmut Ritsch [1]

[1] Leopold Franzens Universität Innsbruck - University of Innsbruck – Austria
[2] Theoretical Physics – Austria

Spontaneous emission in quantum emitters is modified by other atoms nearby, leading to super- and subradiance. We demonstrate the subradiant behaviour of V-type multilevel emitters in close vicinity to each other, withspecific examples being the equilateral triangle and the linear chain at inter-atomic distances smaller than the transition wavelength between the atomic states. For the equilateral triangle it is shown, that a analytical treatment is possible for a very symmetric configuration. In this setup the Hamiltonian has a maximally entangled, antisymmetric eigenstate involving the superpositions of all three atoms which shows subradiance as opposed to superradiance. Moreover, it decouples completely from the vacuum radiation field and therefore does not decay spontaneously. Numerical simulations involving different dipole orientations and interatomic distances are presented and their subradiant behaviour is investigated.

1.56 (Computation) Single-spin relaxation in Si quantum dots induced by spin-valley coupling

Amin Hosseinkhani [1], Guido Burkard [1]

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The spin of isolated electrons in Silicon quantum dot heterostructures is a promising candidate for quantum information processing. While silicon offers weak spin-orbit coupling and nuclear-spin free isotopes, the valley degree of freedom in silicon couples to spin and therefore can degrade the qubit performance by opening a relaxation channel. We have developed the theory of qubit relaxation induced by spin-valley coupling. In this talk, we will discuss the results of our theory for single qubit relaxation in an applied magnetic field and compare our results with experimental findings.

1.57 (Communication) 9.6Tb/s Classical and Quantum Key Distribution (QKD) Co-exitence over a 7-core Multicore Fibre

Emilio Hugues-Salas [1], Rui Wang [1], George T. Kanellos [1], Reza Nejabati [1], Dimitra Simeonidou [1]

[1] University of Bristol – United Kingdom

In this paper, the classical and quantum channel's co-existence is successfully demonstrated including 8x200Gb/s DP-16QAM coherent classical channels in each core and one DV-QKD quantum channel over a 1km 7-core multicore optical fibre. In the proposed system, a total transmission capacity of 9.6Tb/s is achieved by the classical channels on adjacent cores to the assigned core for the quantum key distribution channel. Real-time performance measurements for the classical and quantum channels prove the feasibility of simultaneous transmission and quantum key distribution over a multicore fibre even with the presence of -23dBm classical signals in six adjacent cores and despite the combined inter-core crosstalk to the quantum channel. Detailed studies validate the system co-existence performance, considering classical parameters (BER, received power, OSNR) and quantum parameters (QBER and secret key rate) and reveal error free classical channels transmission without any power amplification at the receiver for a secret key rate of 250b/s.

1.58 (BSCC) Efficient cyclic permutations for qudits

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One of the main challenges in quantum technologies is the ability to control individual quantum systems. This task becomes increasingly difficult as the dimension of the system grows. Here we propose an efficient setup for cyclic permutations Xd in d dimensions, a major primitive for constructing arbitrary qudit gates. Using orbital angular momentum (OAM) states as a qudit, the simplest implementation of the Xd gate in d dimensions requires a single quantum sorter Sd and two spiral phase plates (SPPs). We then extend this construction to a generalised Xd(p) gate to perform a cyclic permutation of a set of d, equally spaced values $|l_0\rangle, \langle l_0 + p|, \ldots, |l_0 + (d-1)p\rangle\}$

1.59 (Communication) The One-Qubit Pad (OQP) for entanglement encryption of quantum information

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The One-Qubit Pad (OQP) protocol is proposed as a maximally efficient scheme for encryption of quantum information with a quantum key consisting of just a single qubit in an arbitrary superposition state. The OQP enables encryption of quantum information of n qubits register (quantum message) with a single qubit key upon introducing a multi-qubit entanglement between the single qubit of the key and the n qubits of the quantum register by iterative application of CNOT gate, always with the same key qubit (control qubit) and subsequent qubits of the quantum register (target qubits). This results in an entanglement of all n+1 qubits, which non-locally locks original quantum information of the message qubits with the single qubit key in a joint, multi-qubit entangled state that cannot be disentangled recovering original quantum information of the message qubits without access to the single qubit key. In order to decrypt quantum register (recover original states of n message qubits) by its disentanglement one needs to have the qubit key and either reverse the protocol (applying CNOT operations in the reversed order) or simply measure the entangled key qubit and depending on the binary projection outcome either straightforwardly recover the decrypted quantum message or its quantum negation (then dealt with by applying quantum negation subsequently on all of the message qubits thus restoring their original states). The OQP protocol is proposed and discussed as a quantum generalization of the One-Time Pad (the Shannon proven information-theoretic secure classical encryption scheme based on the Vernam cipher). The paper analyzes the properties of the OQP protocol pronouncing the differences between the two schemes to show how significantly quantum and classical information differ in this context. The main characteristic of the OQP protocol to use only a single qubit as the key to enable information-theoretic security of n qubits quantum information encryption follows from properties of multi-qubit entanglement, a non-local quantum resource of topological nature. The main application of the OQP protocol and its technologically achievable implementation is to encrypt (or lock) quantum information with the single key qubit in order to prevent any unauthorized access to its original state (both in classical and quantum terms).

1.60 (BSCC) Entanglement Quantum Random Number Generator with public randomness certification

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As QRNGs are gaining attention in the context of efforts in building a scalable, universal quantum computer in the near future, an original new protocol is proposed in randomness generation based on multi-qubit quantum entanglement. The proposed Entanglement QRNG protocol uses a certain type of multi-qubit entanglement of quantum states to produce randomness with previously non-achievable possibility of publicly shifting highly computational resources consuming randomness testing procedures, enabling to perform externally (e.g. by a dedicated institution), the locally unfeasible long-range correlation detection, without unveiling of generated random bits, which remain secret in the information-theoretic sense. The principle of the proposed EQRNG protocol operation is based on the two possible Bell states correlation types randomly projected by a measurement made on a specific 3-qubits entanglement state to either correlated or anti-correlated Bell states of the two remaining qubits, then giving randomnly distinct correlations of bit pairs (while the original 3-qubits state is a fully symmetric superposition of a single qubit's basis states in tensor products with correlated and anti-correlated Bell states). The paper describes the protocol and its implementation in quantum circuits with properties analysis, involving the specific 3-qubits quantum entanglement of generalized Bell state type, topologically inequivalent to other possible different type of maximal level 3-qubits entanglement and easily generalized to multiple-qubits as explained in the paper. The result is characterized in QI formalism and in topological terms. The proposed EQRNG protocol offers for the first time a secret random number generation based on a non-deterministic quantum process with publicly accessible testing for randomness verification and certification without unveiling its secrecy. This corresponds to some extent to the concept of the device independent randomness generation, but in a new way it offers public verification of the randomness, thus enabling any third party to publicly test and verify the randomness of the quantum generated sequence – without accessing its secrecy or distorting it (which is of importance for any practical randomness application in both quantum and classical cryptography).

1.61 (Communication) Simple characterization methods for continuous variable quantum key distribution transmitters

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Quantum key distribution (QKD) provides information-theoretic security of the keys exchanged between two entities communicating on a public channel. The properties of quantum mechanics ensure that any eavesdropper (Eve) leaves a detectable trace. One flavour of QKD utilizes coding of quantum information in the continuous variables (CVs), e.g. amplitude and phase quadratures at the transmitter (Alice) and coherent detection at the receiver (Bob). CVQKD greatly benefits from classical communication, namely in the usage of fast modulators to prepare the signal at Alice and homodyne / heterodyne detection at Bob. Unsurprisingly, several telecom groups have become interested in CVQKD in recent years, which could be responsible for developments such as the replacement of discrete amplitude and phase modulators with an *IQ modulator*, and using phase-diverse heterodyne detectors with a true local oscillator (LO), i.e. the LO is prepared locally in Bob.

In Gaussian-modulated CVQKD, Alice draws pairs of random numbers from a two-dimensional Gaussian distribution with zero mean and *modulation variance* V0 to encode the quadrature components of the coherent states transmitted to Bob. The parameter V0 plays an important role in CVQKD, e.g., Alice needs to optimize V0 according to the channel conditions to obtain the best secret key rate. In practice, it also influences the degree of non-orthogonality of the prepared states. Here we propose and experimentally demonstrate a simple calibration method that Alice can use to measure and track V0 without relying on the information from Bob. The method relies on the simple relationship between the mean photon number (MPN) and V0, i.e., estimation of MPN provides V0.

The utilization of true LO, which may not have the same (center) frequency as Alice's signal, has led to Alice multiplexing a classical *pilot tone* to the quantum signal for sharing phase reference. To be spectrally efficient and avoid inadvertent encoding of information in other sidebands, CVQKD systems must use optical single side modulation (OSSB). By using a model of the IQ modulator and the input waveforms' data, we show how Alice can monitor the degree of OSSB and characterize imperfections such as preparation noise. To conclude, we believe these two methods can improve the overall performance of the CVQKD system.

1.62 (BSCC) Standards4Quantum: Is quantum technology ready for standardization?

Andreas Jenet [1], Samira Nik [2], Fabio Taucer [1], Christian Trefzger [3], Adam Lewis [1], Christian Goroncy [4], Luc Van Den Berghe [2]

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[2] CEN-CENELEC – Belgium
[3] European Commission Communications Networks, Content and Technology – Luxembourg
[4] Deutsches Institut für Normung e.V. – Germany

Quantum technology has made extraordinary progress within the last twenty years, and can potentially act as enabling technology in many fields of our day to day life. Scientists and industries have brought forward first market applications, but still many of the developments are not fully exploited and promising applications are expected within the next years.
An accelerated market uptake of new products, methods and services can be facilitated with standards, as they provide a common basis for mutual understanding. Standards are being elaborated to make trade easier by ensuring compatibility and interoperability of components, products and services and are especially useful for communication, measurement, commerce and manufacturing.
There are different types of standards, some set out requirements that a product, service or process must fulfil, others relate to methods of testing, terminology and definitions, information requirements, or the compatibility of connections.
To join efforts among research, industry and standardisation communities, the European Commission together with the European Standardisation Organisations CEN/CENELEC and with the support of ETSI have launched the 'Putting Science into Standards' initiative. As part of this initiative, workshops are held to facilitate screening of emerging science and technology areas to identify those where concerted research and standardisation activities are required to enable innovation and promote industrial competitiveness.
This work focusses on Quantum Technologies and it will help the European Standardisation Organisations and the Quantum Technology Flagship to identify areas of collaboration and prepare the scene for standardization in quantum-related fields.

1.63 (Communication) Unexpected competition between biexciton and exciton state initialisation processes during resonant two-photon excitation of site-controlled quantum dots with antibinding biexcitons

Gediminas Juska [1], Stefano T. Moroni [1], Simone Varo [1], Iman Ranjbar [1], Agnieszka Gocalinska [1], Emanuele Pelucchi [1]

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Quantum dots (QDs) are on-demand sources of non-classical light – single and entangled photons – a resource which can be exploited to implement quantum information processing. Site-controlled InGaAs QDs grown by MOVPE in inverted pyramidal recesses etched in (111)B oriented GaAs substrates have been already established as very promising candidates due to their intrinsically high symmetry resulting in a high density of entangled photon emitters (Nature Phot. 7,527,2013, Nature Phot. 10,782,2016). All previous results were obtained under non-resonant excitation – a process which is incoherent, noisy and overall inefficient due to the probabilistic population of different excitonic complexes. A typical solution to these issues is resonant two-photon excitation (TPE) and phonon-assisted TPE, which allows for a direct population of the biexciton state with very high fidelity (Phys. Rev. B 91,161302,2015). While never highlighted, a unifying feature of all the to-date reported QDs on which TPE excitation was successfully implemented, is their energetic structure, specifically, a binding biexciton. Furthermore, a theoretical work (Phys. Rev. B 94, 045306, 2016) suggests that, in the specific realistic case of an antibinding biexciton (higher energy than exciton), the biexciton initialisation by TPE has vanishing probability.
Herein we present the first successful experimental study of site-controlled QDs with antibinding biexciton under TPE. We show that two phenomena – direct biexciton and direct exciton initialisation – compete with each other. However, in contrast to theoretical estimations, under coherent TPE (as indicated by Rabi oscillations), biexciton initialisation can be achieved, and it is indeed the most efficient QD population process. Under proper excitation conditions we obtain pure single photon (g2=0.014) and bright polarisation-entangled photon emission. We also discuss a previously unreported acoustic-phonon-assisted exciton initialisation process, showing clear correlations between the laser and the exciton photon polarisation states, a promising attractive phenomenology to initialise an exciton to an arbitrary qubit state.

1.64 (Sensing) Towards spin-squeezing a solid

Krzysztof T. Kaczmarek [1], Géraldine Haack [1], Jean Etesse [1], Alexey Tiranov [1], Tamás Kriváchy [1], Florian Fröwis [1,2], Nicolas Gisin [1], Mikael Afzelius [1]

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Metrology and sensing are a domain of technology, where quantum mechanics offers a demonstrable advantage. On the one hand, the Heisenberg uncertainty principle imposes fundamental limits on measurement precision. On the other, it offers a workaround to these limits using non-classical states as probes, such as squeezed states. In these, the uncertainty of one of the quantum degrees of freedom of a system is reduced below "classical" levels. Spin-squeezing for example can be achieved via a quantum non-demolition measurement of an atomic spin ensemble.
Spin-squeezing has been used to increase the sensitivity and precision of warm and cold atom magnetometers and clocks, but it has never been demonstrated in a solid-state system. One system particularly well suited for quantum metrology using spin-squeezed states are rare-earth ion doped crystals. These offer large spin densities (10ˆ19 ions/cmˆ3) combined with record coherence times (6 hours in Europium), suggesting a potentially huge metrological advantage over previous technologies.
The main challenge for implementing quantum non-demolition measurements in solid-state systems is the large inhomogeneous broadening of the atomic transitions. We use optical hole burning techniques to create a spectrally narrow atomic ensemble in Eu:YSO, which we probe close to resonance with a multi-frequency beam. We demonstrate first experimental data towards an optical quantum non-demolition measurement of the collective spin operator of a solid-state system. With this, we aim at the first solid-state spin-squeezed ensemble, having an unprecedented coherence time, with potential applications in solid-state based quantum metrology and sensing.

1.65 (Sensing) MEMS alkali vapor cells technologies for atomic sensors

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Atomic vapor cells are used in numerous applications in quantum metrology and sensing. In the last decades, pushed by a first generation of miniature atomic sensors, a significant effort has been given to shrink down their size using MEMS microfabrication technologies. In that frame, applications in miniature atomic clocks, atomic magnetometers or atomic gyroscopes were reported. Recently, new emerging applications of MEMS cells, such as field imaging or optical frequency locking, and the parallel development of cold atom spectroscopy in similar devices have given a new technical push to the subject. New advanced development using integrated optical elements have therefore been reported but also new challenges in term of vacuum level and leak tightness have been risen. Here, a report on CSEM wafer-level fabrication and characterization of MEMS atomic vapor cells will be given, these technologies being typically used in the frame of the macQsimal european project. In particular, a characterization of the lifetime improvement of cells filled with CSEM patented RbN3 UV decomposition by Al2O3 coating will be presented. Then, Cu-Cu thermocompression as an alternative bonding method to anodic bonding will be described. This method potentially allows to bond alternative materials such as sapphire and overcome the vacuum level limitations of other materials. Finally, a particular focus will be given to CSEM patent pending gold microdiscs functionalization inserted in the cell cavity as alkali preferential condensation zone. This last technique allows to avoid unwanted interaction of metallic alkali droplets with the interrogation laser. Evidence of long-term frequency stability improvement of an atomic clock using such a cell will therefore be presented.

1.66 (Sensing) Superradiance in ensembles of Strontium-88 with inhomogeneous broadening

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Bad cavity laser is a laser where the linewidth of the cavity mode is broader than the gain profile. Frequency of radiation emitted by such laser is robust with respect to fluctuations of the cavity length, what opens the possibility to create a highly stable active optical frequency standard. We will discuss the possibility of creation of such a stangdard on the babsis of forbidden 3P0-> 1S0 transition in bosonic Sr-88 atoms. Such a transition, generally totally forbidden, can be made slightly allowed in the presence of magnetic field. However, this magnetic field shifts the energy of the 3P0 state, and spatial inhomogenity of this field leads to inhomogeneous broadening of the atomic transition. We consider theoretically influence of such a spatial inhomogenity of the magnetic field, as well as other relevant factors, on the characteristic of the superradiance of ensemble of Sr-88 atoms.

1.67 (BSCC) Nonlinear Analysis of Quantum Systems Using Operator Algebra

Sina Khorasani [1]

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In nonlinear quantum systems such as quantum optomechanics and quantum computing hardware all interactions have a highly nonlinear nature, which makes their analysis extraordinarily difficult using classical schemes.
In absence of nonlinearity, it is highly convenient to use Langevin equations for bosonic operators instead of master equations, which give immediate access to the time-evolution of operators and their momenta, as well as their spectral response. This can lead to a relatively accurate and explicit description of linear quantum interactions in a noisy environment.

However, the case of nonlinearity has to be considered with utmost attention. For nonlinear systems, as long as tiny fluctuations around equilibrium points are of interest, then linearization of Langevin equations around equilibrium values is expected to work well. But two situations need careful consideration:

(a) When either the oscillating amplitudes are not small, or the nonlinearity is too strong because of large amplitude excitations.
(b) When the nonlinearity leads to observable effects even when only fluctuations are considered. This is the actual case in domains such as standard and quadratic quantum optomechanics.

Side-band Inequivalence [2] is an example where pure nonlinearity leads to symmetry breaking. One would therefore need to develop a convenient mathematical tool which enjoys freedom and convenience of Langevin equations, at the same time is not fully numerical, and is also able to deal with three basic properties: Quantumness, Openness, and Randomness.

Based on the extension of Langevin equations to products of ladder operators, the **Method of Higher-order Operators** recently developed by the author meets all of the above concerns [1-3].

[1] S. Khorasani, *Photonics*, vol. 4, no. 4, 48 (2017).
[2] S. Khorasani, *Scientific Reports*, vol. 8, 11566 (2018).
[3] S. Khorasani, *Scientific Reports*, vol. 8, 16676 (2018).

1.68 (Communication) Versatile micro-optical bench for photonic integration in quantum technology

Moritz Kleinert [1], Hauke Conradi [1], Madeleine Nuck [1], David De Felipe [1], Martin Kresse [1], Crispin Zawadzki [1], Norbert Keil [1], Martin Schell [1]

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Generation and detection of single and entangled photons for communications applications such as Quantum Key Distribution are well studied in laboratory environments. These set-ups usually employ free-space optics for the coupling of light into bulk elements such as non-linear optical crystals. While this approach yields high efficiencies and is well proven, it is difficult to integrate with existing solutions for photonic integrated circuits used in communications. The key to scaling towards future production of components for quantum communications applications is the miniaturization of the free-space set-ups by means of a versatile micro-optical bench and the integration with existing photonic technology platforms.
The polymer-waveguide-based PolyBoard platform of Fraunhofer HHI combines readily available optical functionalities (e.g. multi-mode interference couplers, Bragg gratings, and thermo-optical elements) with a spectrally broad transparency (visible to near infrared) and the possibility to insert micro-optical components (e.g. thin-film elements and GRIN lenses) into etched slots and grooves on the integrated chip. By means of two collimating GRIN lenses, an on-chip free-space section is formed, in which bulk optical crystals can be placed. By inserting non-reciprocal BI:YIG crystals in combination with thin-film elements for polarization handling, novel on-chip optical isolators with extinction ratios up to 33 dB were successfully demonstrated.
By employing non-linear instead of non-reciprocal optical crystals, well-known set-ups for quantum communications can be miniaturized and implemented on chip level. Due to the broad spectral transparency of the polymer material, additional integrated waveguides for pump, signal, and idler can be realized on the same chip. The poster will present this integration approach as currently pursued within the QT flagship project UNIQORN and lay out prospects for future applications in other fields of quantum technology.

1.69 (Sensing) Recovering quantum gates from few average gate fidelities

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Characterizing quantum processes is a key task in the development of quantum technologies, especially at the noisy intermediate scale of today's devices. One method for characterizing processes is randomized benchmarking, which is robust against state preparation and measurement errors and can be used to benchmark Clifford gates. Compressed sensing techniques achieve full tomography of quantum channels essentially at optimal resource efficiency. In this work, we show that the favourable features of both approaches can be combined. For characterizing multiqubit unitary gates, we provide a rigorously guaranteed and practical reconstruction method that works with few average gate fidelities measured with respect to random Clifford unitaries.

In our proofs we exploit new representation theoretic insights on the Clifford group, develop a version of Collins' calculus with Weingarten functions for integration over the Clifford group, and combine this with proof techniques from compressed sensing.

1.70 (BSCC) Polycrystalline diamond for quantum technology on a large scale

Peter Knittel [1], Christoph Schreyvogel [1], Julia Langer [1], Christian Giese [1], Volker Cimalla [1], Christoph Nebel [1]

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Quantum technologies based on diamond have gained significant importance over the past years. Defects ins diamond grown by chemical vapor deposition (CVD) are nowadays experimentally controlled and have been minimized to realize so-called electronic or quantum grade single crystalline diamond substrates. Such substrates are typically used for e.g., spin devices capable of room temperature operation, and pave the way for applications in quantum sensing and computing. However, these single crystalline substrates are obtained from homoepitaxial growth and hence are costly, strongly limited in their size (typical dimension is 4x4 mm2) that impairs their processability, and often difficult to obtain in large quantity. Polycrystalline diamond films can be grown at wafer scale, i.e., processable with standard cleanroom technologies, on various substrates with high purity. These films consist of single crystalline diamond grains and grain boundaries. The physical properties of the material are mainly determined by the grains and hence this material is a suitable matrix for e.g., nitrogen vacancy (NV) centers. Indeed, it has already been demonstrated that long coherence times NV centers, which depends on the level of impurities and defects, can be readily achieved in polycrystalline diamond. Here, we present polycrystalline diamond films grown via CVD and doped with nitrogen during growth to control the incorporation of NV centers. Material characterization by photoluminescence measurements will be presented. Additionally, microfabrication techniques for further processing of such diamond films, e.g., to obtain free standing membranes or nanostructured surfaces, will be shown.

1.71 (Sensing) Element-Resolved Nanoscale NMR Spectroscopy using Nanodiamond Quantum Sensors

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Conventional nuclear magnetic resonance (NMR) spectroscopy relies on acquiring a signal from a macroscopic volume of identical molecules to provide structural information on the single molecule level. Transferring this technique to nanoscale sample sizes would enable the probing of local chemical environments in biologically relevant samples on the sub-cellular scale. NMR devices based on nitrogen vacancy (NV) centers implanted in bulk diamond have shown single nuclear spin sensitivity and resolution required to determine chemical structure, but their detection volume extends only a short range (nanometers for the most sensitive devices) above the diamond surface. This narrow range precludes NMR measurements with nanoscale resolution inside thicker structures, such as cells. We demonstrate the detection of NMR signals from multiple nuclear species in a (19 nm)ˆ3 volume using a versatile NV-NMR device inside a diamond nanocrystal of _˜25 nm diameter. We are able to sense _˜1000 molecules in our sensing volume. While the measured NMR signal amplitude is subject to systematic error from the geometric variability of nanodiamonds devices, this error can be corrected for using an in-situ calibration scheme based on exploiting the signal from a thin layer of reference nuclei on the diamond surface. With this added capability, such devices could be applied to complement fluorescent-dye based indicators that are widely used to measure the concentration of chemical species within cells, but suffer from several challenges, including bleaching, low chemical specificity, high toxicity and the need for careful calibration to factors like temperature and pH. Our devices may thus provide a useful alternative because of their robustness to photobleaching and environmental changes, low toxicity, and their ability to measure multiple species with high specificity.

1.72 (Computation) Strong Microwave Photon Coupling to the Quadrupole Moment of an Electron in Solid State

Jonne Koski [1], Andreas Landig [1], Pasquale Scarlino , Maximilian Russ [2], José Uriel [3], David Van Woerkom [1], Christian Reichl [1], Werner Wegscheider [1], Mark Friesen [3], Susan Coppersmith [3], Guido Burkard [2], Andreas Wallraff [1], Thomas Ihn [1], Klaus Ensslin [1]

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The implementation of circuit quantum electrodynamics (cQED) allows coupling distant qubits by microwave photons hosted in on-chip resonators. Typically, the qubit-photon interaction is realized by coupling the photons to the electrical dipole moment of the qubit. A recent proposal [1] suggests storing the quantum information in the quadrupole moment of an electron in a triple quantum dot. This type of qubit is expected to have an improved coherence since the qubit does not have a dipole moment and is consequently better protected from electric noise. We report the experimental realization of such a quadrupole qubit hosted in a triple quantum dot in a GaAs/AlGaAs heterostructure. A high-impedance microwave resonator is capacitively coupled to the middle of the triple dot to realize interaction with the qubit quadrupole moment. We demonstrate strong quadrupole qubit-photon coupling with a qubit-photon coupling strength of 130 MHz and a qubit decoherence rate of 30 MHz. Furthermore, we observe improved coherence properties of the qubit when operating in the parameter space where the dipole coupling vanishes.

M. Friesen *et al.*, Nature Comm. **8**, 15923 (2017)

1.73 (Simulation) Why is it called the Density Matrix Renormalization Group?

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Over the past 25 years, analyzing quantum problems from an entanglement perspective has become an option due to tensor networks. Since entanglement is not a traditional perspective given to quantum systems, it is important to motivate the resulting algorithms clearly so their results can be understood better. To understand why one of the most popular methods, known as the density matrix renormalization group (DMRG) method, takes this name, a discussion of phase transitions on a Ising lattice will be conducted with an efficient implementation of a Monte Carlo simulation followed by a discussion of the behaviors of a lattice in relation to the renormalization group (comparing both the Kadanoff and Wilson pictures), and then finally how a system can be partitioned into sectors and solved by considering the density matrix. The connection with information theory will be discussed.

Chapter 2

Session 2: Wednesday and Thrusday

2.1 (Sensing) Atom interferometry for high sensitivity in inertial measurements

Arnaud Landragin [1], Franck Pereira Dos Santos [1], Xavier Alauze [1], Matteo Altorio [1], Carlos Garrido-Alzar [1], Remi Geiger [1], Romain Karcher [1], Sébastien Merlet [1], Leonid Sidorenkov [1]

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Atom interferometry covers applications in metrology, inertial navigation and geophysics. It combines both intrinsic high sensitivity and accuracy thanks to the high level of control of the atom-laser interaction. Beyond the proof of principle, specific developments are needed in order to fulfill these expectations for real applications.
One of the first major achievements so far in term of application is the realization of absolute atomic gravimeters. After a first period of development and validation of their performances, we will show that recent developments based on the use of ultra-cold atom sources allows reaching record-breaking accuracies at the level of 10-8m.s-2 [1].

Two important limitations for applications are the low bandwidth and dead times between successive measurements. We have demonstrated efficient methods to operate a large area matter-wave gyroscope of 11 cm2without dead times [2] and at a sampling frequency of 3.75 Hz [3] leading to record sensitivities of 32 nrad.s–1.Hz–1/2, which allows us to characterize and stabilize systematic effects below 3×10–10rad.s–1after 15 000 seconds of integration time. Such level of stability competes with best long term stabilities obtained with fiber-optics gyroscopes.

Beyond the developments of cold atom interferometers using free falling atoms, significant efforts are carried out in order to propose and demonstrate alternative methods based on trapped or guided atoms with dipole [4] and/or magnetic traps [5]. Such interferometers benefit from extending interrogation time and might lead to the realization of more compact sensors. As they keep the atom better localized, they are also promising candidates for applications to inertial navigation and local force measurements. We will present our latest results on an interferometer based on trapped atoms in an optical lattice [6], which features the state of the art force sensitivity, of 7.10-30N/Hz1/2.

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[5] C. L. Garrido Alzar, PRA **97**, 033405 (2018)
[6] X Alauze, et al, NJP **20** 083014 (2018).

2.2 (BSCC) Electron cooled cryogenic platform for quantum devices

Janne Lehtinen [1], Mika Prunnila [1], Emma Mykkänen [1], Antti Manninen [1], Leif Grönberg [1], Andrey Timofeev [1], David Gunnarsson [1], Antti Kemppinen [1], Alberto Ronzani [1], Andrey Shchepetov [1]

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Refrigeration is an important pillar of quantum technology: due to the low energy of most fundamental quantum excitations, several practical implementations outright require temperature scales well below 1 K. For quantum electronics, this is achieved with expensive dilution refrigerators, where a massive inner sample space is cooled down to sub-100 mK temperature over the course of tens of hours. On the other hand, several quantum electronic devices only require their miniaturized active elements to reach such low temperature.
Here we demonstrate a proof-of-concept device capable of cooling an individual macroscopic silicon chip by 40 % from bath temperature of 170 mK [1]. The operation of the cooler is based on superconducting thermionic electron refrigeration, a cryogenic analogue to room-temperature thermoelectric coolers. In particular, our approach leverages suspending the silicon chip [1] with semiconductor-superconductor tunnel junctions [2,3]. The interfacial thermal boundary resistance, due to the lattice mismatch between the superconducting electrodes and the cooled chip [1], provides phonon isolation and the superconducting energy gap enables electron cooling by quasi-particle filtering.

We provide simulations of a refrigerator, that has been improved by sophisticated material and phonon engineering and multistage cascade structure, to enable cooling even from 1.5 K to below 100 mK. Achieving this target would allow for significant savings over conventional refrigeration systems. Compared to dilution refrigeration (slow, expensive, heavy and unsustainably dependent on the rare 3He isotope), our approach reduces cooldown times to few seconds and benefits from intrinsically maintenance-free operation. Finally, its overall mass and size are much better suited to practical turn-key systems and are especially ideal as compact payloads for space missions.

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2 J. Muhonen, M. Meschke, J. Pekola, Rep. Progr. Phys. **75**, 046501 (2012).
3 D. Gunnarsson *el al.*, Sci. Rep. **5**, 17398 (2015).

2.3 (Computation) Foresight for quantum computing: a survey of stakeholders' views

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The JRC has conducted a study of stakeholders' professional views on quantum computing, emphasising the implications for European public policy. Issues addressed were: drivers and promise of applications, timescales, funding, commercialisation, training, broader social and economic implications, hardware platforms, algorithms and software, quantum computing's place in the future IT landscape, and areas of European strength and weakness. The study employed the Real-Time Delphi method, an online questionnaire-based technique which allows participants to see the range of opinions as it develops and modify their own responses. Participants could give quantitative replies to structured questions and also express their views as free text. For most questions, around 100 people replied, being about half those invited: the majority work in Europe and declared a high level of competence in the field. Despite the use of a method intended to foster consensus, a wide range of views was recorded for the key technical questions. However, a clear agreement emerged on the need to concentrate public funding on basic research, because it is still too early to commit to a single path forward. This position is somewhat misaligned with the stated rationale of the flagship, which presupposes a level of technology readiness high enough to yield commercial products in the near-to-medium term. Conversely, the majority view is that the timescale for practical applications is of 10-15 years. Respondents highlight scientific uses in quantum simulation, chemistry, and materials science, and see as the next most promising IT tasks such as database search, machine learning and pattern recognition, and computational tasks such as optimization. The consensus is that the societal impact of quantum computing will be both profound and benign. This was to be expected: most people who chose to reply are members of the quantum computing scientific community, and likely to hold a positive and optimistic view of the technology.

2.4 (Sensing) A gas sensor based on Rydberg excitations

Robert Loew [1], Johannes Schmidt [1], Patrick Kaspar [1], Fabian Munkes [1], Denis Djekic [1], Patrick Schalberger [1], Holger Baur [1], Tilman Pfau [1], Jens Anders [1], Norbert Frühauf [1], Edward Grant [2], Harald Kübler [1]

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Sensitive and selective gas sensors become increasingly important for the analysis of the exhaled breath of mammals. Our scheme is based on the excitation of Rydberg states in the molecule of interest. Subsequent collisions with the background gas and predissociation will lead to ionization. The emerging charges can then be measured as a current. The occurrence of a current is an unequivocal indication of the presence of the molecule under consideration. We demonstrate technology readiness level 3 of our scheme at the example of the detection of 100 ppb Rb in a background gas of N2 with a sensitivity of 10 ppb/Hzˆ1/2. We further experimentally verify the applicability in real life on the detection of nitric oxide in a gas mixture up to ambient pressure.

[1] J. Schmidt, et al., SPIE 10674 (2018)
[2] J. Schmidt, et al., Appl. Phys. Lett. 113, 011113 (2018)

2.5 (Sensing) Single molecules in Planar Optical Antennas: Efficient Single-Photon Sources for Free-Space and Fiber-Based Operation in Quantum Optics and Metrology

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Practical implementations of quantum technologies, ranging from optical quantum computing to metrological measurements, suffer from the lack of high-rate, on-demand sources of indistinguishable single photons.
We will discuss a simple and versatile planar optical antenna, showing both theoretical and experimental evidence of low-loss ($<$ 20%) beaming of the radiation from a single quantum emitter into a narrow cone of solid angles in free space, which allows in principle up to 50% coupling into a single-mode fiber.
In particular, we will first present an experimental implementation of the design operated at room temperature, exploiting Dibenzoterrylene molecules (DBT) hosted in a crystalline anthracene matrix (Ac) [1]. The DBT:Ac system is particularly suitable for this task, due to its outstanding photo-physical properties (i.e. long-term photostability both at room and cryogenic temperature, lifetime-limited emission at cryogenic temperatures, 780 nm operating wavelength) demonstrated in 50 nm-thick crystals [2] and recently also in nanocrystals [3]. Moreover, single photons from DBT molecules and similar [4] result very appealing concerning quantum communication and computation protocols which involve quantum memories, due to the unmatched stability and narrowness of their spectrum (below 100 MHz).
Then we will report on our theoretical study to determine the ultimate performances attainable with such design in case of operation in cryogenic environment, exploring materials and fine tuning of geometrical parameters. We will finally discuss our recent results about a single-mirror antenna operating at cryogenic temperature. We demonstrate a photon flux in the Fourier-limited line higher than 1MHz at detectors, and coupling of fluorescence into single-mode fibers up to 46%.
These results open to the deploiment of our system both in quantum optics experiments requiring deterministic single-photon sources and in metrology, in particular for a new operative definition of the candela (EMPIR project "SIQUST" [5]).
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[4] P. Siyushev et al., Nature **509** (7498), pp.66 (2014)
[5] https://www.siqust.eu/

2.6 (BSCC) Heat-Bath Algorithmic Cooling with Thermal Operations

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Heat-Bath Algorithmic Cooling is a technique for producing pure quantum systems by utilizing a surrounding heat-bath. Here we connect the study of these cooling techniques to the resource theory of thermal operations, enabling us to derive provably optimal cooling protocols under a variety of experimental restrictions on the available control. For qubit systems, we find that a surprisingly simple, optimal protocol consisting of repeated application of a Pauli X unitary and a thermal operation can achieve purity converging exponentially quickly to one. What is more, this thermal operation can be well approximated using a Jaynes Cummings interaction between the system and a single thermal bosonic mode and we consider experimental implementations of this. In addition, we investigate the role of quantum coherence and non-Markovianity in cooling protocols and extend our results to higher dimensional systems. Finally, by considering the role of correlations with auxiliary systems in cooling, we show that purity arbitrary close to one can be achieved in a fixed number of operations. Our results serve to find practical applications for the resource theoretic approach to quantum thermodynamics and suggest relevant experimental implementations.

2.7 (Computation) Quantum unsupervised algorithms for classification

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Quantum machine learning carries the promise to revolutionise information and communication technologies. In clustering (unsupervised machine learning), the task is to group elements of the training set that are deemed similar according to some measure of similarity.
We present a new algorithm for clustering: Q-means. This algorithm is the quantum version of k-means, the most fundamental and ubiquitous clustering algorithm. Being an iterative algorithm, Q-Means has convergence and precision guarantees similar to k-means. Our algorithm is polylogarithmic in the number of vectors in the dataset, thus with an exponential separation with respect to classical algorithms. We introduce carefully the toolbox used in quantum machine learning: procedure to perform quantum linear algebraic operations, the QRAM circuit as an access model on the data, and routines to calculate distances - which we refined.
We report our simulations of the quantum algorithm (including errors) on a common dataset used to benchmark classification algorithms - and show that we can get accuracy comparable to the classical case. We estimated the running time by analyzing the parameters on which the running time depends on a real dataset. They scale favorably, thus ascertaining the efficiency of our algorithm.

We report also some steps in the direction of generalizing q-means to fitting gaussian mixture model with a quantum computer.

We review recent result on supervised classification (namely Quantum Slow Feature Analysis and Quantum Frobenius Distance Classifier)[1].

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[2] Iordanis Kerenidis, Alessandro Luongo, Jonas Landman, Anupam Prakash. https://arxiv.org/abs/1812.0358

2.8 (Simulation) Excitonic complexes in layered semiconductors

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Layered transition metal dichalcogenides (TMDs) are a new material platform for tailored quantum emission[1,2]. Each TMD layer is composed of a layer of transition metal atoms such as Mo or W, sandwiched between two layers of chalcogens such as S or Se. TMD monolayers have a direct gap[3,4] and strong optical absorption[5,6,7] because of bound quasiparticles, such as excitons[8,9], trions[10,11], biexcitons[12,13], and quintons[14,15]. These can be used to generate entangled photon pairs for quantum computing. To understand the possible excitonic complexes, we use diffusion quantum Monte Carlo to calculate the properties of assemblies of interacting quantum particles using random sampling of the full many-body Schrödinger equation [16]. We provide binding energies (BE) for Mott-Wannier models of excitonic complexes in layered materials. We also provide interpolation formulas giving the BE as functions of the electron and hole effective masses and in-plane polarizability, in a good agreement with experiment[14,15,17].

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M. Szyniszewski et al. *Phys. Rev. B* **95**, 081301 (2017).

2.9 (Communication) Interfacing an electron with a nuclear ensemble: Towards a built-in quantum memory per qubit

Claire Le Gall [1], Dorian Gangloff [1], Gabriel Ethier-Majcher [1], Constantin Lang [1], Emil Denning [1,2], Jonathan Bodey [1], Daniel Jackson [1], Edmund Clarke [3], Maxime Hugues [4], Mete Atatüre [1]

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Coherent excitation of an ensemble of quantum objects offers the opportunity to realise robust entanglement generation and information storage in a quantum memory[1]. Thus far, interfacing with such a collective excitation deterministically has remained elusive owing to the difficulty of controlling a probe spin in the midst of a complex many-body system. Here, we first use an electron to cool the mesoscopic nuclear-spin ensemble of a semiconductor quantum dot[2] to the sideband-resolved regime[3]. We then implement an all-optical approach to access the individual quantised electronic-nuclear spin transitions. Finally, we perform coherent optical rotations of a single collective nuclear spin excitation corresponding to a spin-wave called a nuclear magnon. Driving the magnon transition resonantly, we measure a coherent interaction between the electron and the nuclear spin ensemble, which creates at periodic intervals a symmetrically-distributed excitation among all nuclei, forming the basis of multipartite entanglement as found for Dicke states. These results constitute the building blocks of a robust local memory per spin qubit and promise a solid-state platform for quantum-state engineering of isolated many-body systems.

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2.10 (Simulation) Dissipative state preparation of spin-entangled fermionic states in optical lattices

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The robust generation of highly-entangled states in AMO systems with high fidelities, with applications ranging from quantum simulation to metrology, constitutes one of the main challenges in current experimental setups. We consider the use of dissipative dynamics in analogy to quantum optics, engineering the coupling between the system and its environment. We propose a new scheme for the systematic preparation of spin-symmetric states by making use of the statistics of fermionic atoms in an optical lattice embedded in a BEC reservoir. The preparation of such states relies on the corresponding coupling between spin and spatial symmetries due to the global antisymmetry of the fermionic wavefunction. We introduce a stroboscopic scheme that filters the spin symmetry of the wavefunction by combining a Raman transfer to a higher Bloch band and the dissipative cooling due to the coupling to the BEC. This scheme generates a completely spin-symmetric state preserving the initial particle number overcoming previous proposals that were based on two-body loss. We also characterise the properties of the spin-entangled states and its utility towards a Ramsey Spectroscopy experiment through the Quantum Fisher Information and test the robustness of the scheme against experimental imperfections.

2.11 (Communication) Integration of quantum random number generators in CMOS technology

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The present work would show progress, main advantages and future perspective of Quantum Random Number (QRNG) generators integrated in standard CMOS technology.
QRNGs offer a clear advantage with respect to classical true RNGs (TRNG), being fundamentally random and easily modelled through simple schemes. Nevertheless, the real bottleneck of this technology is the relevant cost of present solutions, preventing their spread in large consumer markets.

The present work shows recent solutions proposed in the literature to integrate QRNGs, based on photonics, in a standard CMOS technology in order to compact and reduce their cost. In general, the process of integration has two main benefits: the scalability and the miniaturization. Concerning scalability, the idea to integrate more QRNGs working in parallel in an independent way into the same chip, has been shown a successful solution for increasing the rate of the generation of random bits up to Gbps [1-2]. The miniaturization instead is related to the possibility to integrate not only the detection but also the post-processing and on-the fly test on the same device, allowing to increase the robustness towards possible physical attacks.

In the view to integrate and increase the compactness of the system, some authors recently provided the use of SiLED in a system on package solution [3] or, even, in a monolithic solution [4-5]. This last perspective, i.e. the integration of both source of photons and detectors into the same substrate, it paves the way towards a low cost solution, with comparable performance with respect to TRNGs.

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2.12 (Communication) Quantum Research CubeSat (QUARC)

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The realisation of the full quantum internet will require the development of a number of diverse enabling technologies the most prominent being the capability of establishing satellite quantum links over intercontinental scale. The (Communication) Quantum Research CubeSat (QUARC) is a proposal to offer secure quantum key distribution (QKD) communication from a 6U nanosatellite platform. CubeSats compared to traditional, large satellite platforms, are relatively low cost and therefore are ideal candidates to form large satellite constellations offering greater coverage and mitigating some of the risk associated with poor performance due to cloud cover. In this work, we present the results of our analysis in terms of key provision and the results of a preliminary hardware development of the acquisition pointing and tracking (APT) system to support future in-orbit demonstration.
We propose a mission addressing the downlink QKD from a constellation of trusted satellites to a network of optical ground stations (OGS) within the UK. The mission achieves high levels of coverage and regular revisit to the gateways by choosing a low Earth orbit (LEO), with orbital characteristics that satisfy both Earth- and Sun-synchronism. We developed a numerical simulation for the orbital passages that incorporate sunrise and sunset conditions and historical cloud cover statistics. This analysis is fed into an in-depth model of the atmospheric channel in order to produce an estimation for the rate of secret key incorporating also finite block size effects.
Low transmitter pointing error is a crucial requirement to successfully deliver weak coherent pulses in the OGS field of view. In our system, pointing is realised via a two-stage process. First, reaction wheels perform coarse pointing of the body-mounted telescope, based on attitude determination via star tracker; the aim of this first stage is to rotate the satellite in order to produce an image of the uplink-beacon (sent by the OGS) in the field of view of the on-board beacon camera. The beacon camera is then used to drive the fine pointing stage consisting of a micro-electromechanical system micromirror that acts as a fast steering mirror. Our APT system has proved to be effective in suppressing turbulence and has achieved few micro radiant of pointing precision suitable for LEO downlink.

2.13 (Simulation) Collective effects in photon gases: the cases of cold atoms and plasmas

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Photons propagating in complex media significantly modify their properties. Among the prominent examples, we may highlight the effective mass and the photon-photon interaction as the main ingredients leading to collective behaviour of photon gases. In this talk, we discuss two situations where the modifications of the photon dispersion may be drastic: i) near-resonant photons in cold atomic clouds, and ii) photons in warm plasmas. In the first case, we argue that resonance effects lead to a diffusive transport of photons inside the medium, which eventually becomes unstable. Experimental investigations suggest that such diffusive instabilities are at the basis of a novel source of photon turbulence, the "photon bubbling" turbulence. In the second case, photons undergo both direct and inverse Compton scattering processes with the plasma electrons, and preliminary theoretical studies indicate that photon Bose-Einstein condensation is possible. We finally comment on the possibility of exploiting the collective behaviour of photons in these media to simulate astrophysical situations in the lab.

2.14 (BSCC) Rise and Fall of a Bright Soliton in an Optical Lattice

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We study an ultracold atomic gas with attractive interactions in a one-dimensional optical lattice. We find that its excitation spectrum displays a quantum soliton band, corresponding to N-particle bound states, and a continuum band of other, mostly extended, states. For a system of a finite size, the two branches are degenerate in energy for weak interactions, while a gap opens above a threshold value of the interaction strength. We find that the interplay between degenerate extended and bound states has important consequences for both static and dynamical properties of the system. In particular, the solitonic states turn out to be protected from spatial perturbations and random disorder. We discuss how such dynamics implies that our system effectively provides an example of a quantum many-body system that, with the variation of the bosonic lattice filling, crosses over from integrable nonergodic to nonintegrable ergodic dynamics, through nonintegrable-nonergodic regimes.

2.15 (Simulation) From curved spacetime to spacetime-dependent local unitaries over the honeycomb and triangular Quantum Walks

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A discrete-time Quantum Walk (QW) is an operator driving the evolution of a single particle on the lattice, through local unitaries. Some QW admit, as their continuum limit, a well-known equation of Physics. In [1] the QW is over the honeycomb and triangular lattices, and simulates the Dirac equation. We apply a spacetime coordinate transformation upon the lattice of this QW, and show that it is equivalent to introducing spacetime-dependent local unitaries -whilst keeping the lattice fixed. By exploiting this duality between changes in geometry, and changes in local unitaries, we show that the spacetime-dependent QW simulates the Dirac equation in $(2 + 1)$–dimensional curved spacetime. Interestingly, the duality crucially relies on the non linear-independence of the three preferred directions of the honeycomb and triangular lattices: The same construction would fail for the square lattice. At the practical level, this result opens the possibility to simulate field theories on curved manifolds, via the quantum walk on different kinds of lattices.

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2.16 (BSCC) Measuring individual and ensemble lifetimes of high-lying Rydberg states for quantum simulations

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Rydberg atoms have become a versatile tool for quantum simulation in recent years. Their long lifetimes and strong van-der-Waals and dipole interactions are ideal for simulating the dynamics of many-body systems. For high-lying Rydberg states, however, transitions between Rydberg states induced by black-body radiation become and important process that can strongly affect the experimental outcomes. In order to study those processes for Rydberg states with principal quantum number $n > 60$, for which state-selective field ionization becomes difficult to apply, we use a hybrid method involving state-selective depumping via a fast-decaying intermediate state and field ionization. This allows us to measure both the individual lifetime of a target Rydberg state and that of the ensemble of Rydberg states populated via black-body radiation. We find that for Rydberg S states the individual lifetimes agree well with theoretical predictions up to n=90, but deviate substantially for higher n. The ensemble lifetimes agree with a numerical model including all possible black-body induced transitions and essentially approximate the target state lifetime at zero temperature. For Rydberg D states, we find large deviations from the theoretical predictions between n=60 and n=90. Possible reasons for those deviations are currently under investigation.

2.17 (Simulation) The quantum advantage of entangled bosons in a ring-shaped potential

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We consider a system of attractively interacting neutral bosons flowing in a ring-shaped potential of mesoscopic size. We find that the persistent currents have an N-fold reduction of periodicity, with N being the number of particles in the ring. Such effect arises because of the quantum correlations in the many-body bound state. In the mean field case, the usual periodicity of the current is recovered. Our results imply that the matter-wave current in our system is able to react to very small changes in artificial gauge fields or to a physical rotation. In this way, we put the basis to devise a novel generation of gyroscopes with quantum-enhanced sensitivity.

2.18 (Computation) Large QHC logic gate design

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After the seminal work of A. Aviram and M. Ratner [1], a few hybrid molecular electronic circuits have been proposed for molecular electronics [2]. The semi-classical mono-molecular approach was then introduced [3] where the entire arithmetic and logic unit (ALU) of a calculator was proposed to be embedded in a single very large molecule (Y. Wada proposed the same with electronic circuits to be constructed atom by atom on a surface [4]). A more chemically realistic single-molecule 2-digit full adder was proposed by J. Ellenbogen [5].
To avoid copying the circuit electronic circuit architecture to design such molecular ALU, a new quantum control protocol, called the Quantum Hamiltonian Computing approach (QHC) was proposed in 2005 [6]. It does not involve dividing the molecular structure into individual elementary gates (or switches or transistor or qubits) and still belongs to the same family of control theory than the one generally applied to quantum computer.

Following this new QHC approach, 2-inputs/1-output (OR, NOR, AND, NAND, XOR, NXOR) QHC Boolean logic gates were designed [7] opening the experimental realization of molecule logic gate using starphene molecules like the recent NAND gate [8,9]. We will recall the basic of the QHC design to reach single molecule logic gate chemical structures and will present our new approach for larger QHC gates like the 2-inputs/2-outputs half adder and 3-input/2-output full adder within two different output reading protocols.

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2.19 (Computation) High stability micro-cavity setup for quantum optics at low temperatures

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High-finesse, open-access, mechanical tunable, optical micro-cavities [1] offer a compelling system to enhance light matter interaction in numerous systems, e.g. for quantum repeaters, single-photon sources, quantum computation and spectroscopy of nanoscale solid-state systems. Combining a scannable microscopic fiber-based mirror and a macroscopic planar mirror creates a versatile experimental platform. A large variety of solid state quantum systems can brought onto the planar mirror, analyzed, addressed individually, and (strongly) coupled to the cavity by moving the microscopic mirror [2,3]. With simple mechanical tuning of the cavity length, the resonance frequency can be adapted to the specific quantum system of interest.

However, the flexibility of the mechanical degrees of freedom bears also downsides. Especially in strongly vibrating environments, e.g. inside close-cycle cryostats, fluctuations of the cavity length on the picometer scale are often enough to prevent the use of high-finesse cavities desired in quantum optics experiments.

We present our successful approach to realize a fully 3D-scannable, yet highly stable cavity setup, which features a passive stability on the femtometer scale under ambient conditions. Furthermore, we present stable operation inside a closed cycle cryostat.

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2.20 (Sensing) Creation of spin defects in wide bandgap semiconductors for quantum sensing by particle irradiation

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Negatively charged nitrogen-vacancy (NV) centers in diamond and negatively charged silicon vacancy (VSi) in silicon carbide (SiC) are known as spin defects which can de applied to quantum sensing. For quantum sensing, it is important to develop the creation methods of such spin defects effectively, *e.g.* high concentration for high sensitivity and certain locations for local area sensing. Particle irradiation such as electrons and protons are regarded as a useful method to create spin defects with wide concentration ranges as well as specific locations. We created VSi in certain locations of SiC pn diodes without the significant degradation of diode characteristics using proton beam writing (PBW) technique. The luminescence properties of VSi was controlled by device operation (current injection by applying forward bias). Optically detected magnetic resonance (ODMR) for VSi in a SiC pn diode was also observed based on a standard photoluminescence technique. For high concentration spin defects, we used irradiation of electron beams with MeV range. Combining NV centers created in diamond by electron irradiation with coplanar waveguide resonator, we developed an optical system with a detection volume of 1.4x10-3 mm3. As a result, we demonstrated AC magnetometry with a sensitivity of 3.6 pT/(Hz)1/2 in which a decoupling pulse sequence, XY16, was applied to extend spin coherence time T2 to 27 times longer than the original value. In the presentation, we will also introduce irradiation techniques that we developed such as high temperature electron irradiation to reduce residual defects and nitrogen ion microbeam irradiation to create NV centers at certain locations in diamond.
This study was partially supported by MEXT Q-LEAP and CAO PRISM.

2.21 (Simulation) Computation of molecular spectra on IBM Q quantum processors

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[2] IBM Research – Switzerland
[3] IBM Research Zürich – Switzerland

In this work we illustrate the use of the open source IBM Quantum Information Software Kit (Qiskit) to compute ground and excited states energies of relatively simple molecules (e.g., hydrogen, lithium hydride and water molecules) on a quantum simulator as well as on a real hardware (IBM Q Experience). Within the second quantization formalism of quantum mechanics, the electronic structure Hamiltonian of any molecular system can be mapped into the corresponding qubit Hamiltonian. The implementation of this mapping in the particle-hole (p/h) picture was shown to improve the accuracy and the speed of convergence of ground state properties (e.g., energy, dipole moments, etc.). The ground state electronic energy was obtained using the variational quantum eigensolver (VQE) algorithm, where the exponentially hard part of the problem (the sampling of the wavefunction space) and the calculation of the Hamiltonian expectation values are performed in the quantum hardware while the parameter optimization is done on a classical computer. The trial wavefunctions are prepared using the Coupled Cluster expansion [Barkoutsos et al., Phys. Rev. A 98, 022322]. Starting from the optimized ground state wavefunction, we also explored ways to compute efficiently the corresponding excited states energies.

2.22 (BSCC) Quantum Link-Prediction for Complex Networks

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Link prediction in complex networks consists in finding which pairs of nodes are likely to be connected, taking advantage of the information encoded in the topology of each network. Complex networks are a general description that fits many physical, social, biological and information systems, giving the problem of link prediction multidisciplinary implications. Research so far has been focused on the application to social and biological networks. Experiments to map the full structure of biological networks (e.g. protein-protein interactions) are very challenging, costly and time consuming, and large amounts of data is still missing. Link prediction methods are not only a key computational tool to aid these efforts in understanding complex biological systems, but also very useful for other studies of time-varying complex networks, as for example social networks.

Most link prediction tools developed so far are based on the Triadic Closure Principle (TCP), assuming that two nodes are more likely to connect if they have many direct connections in common. Recently it has been shown that, despite its dominant use in biological networks, the TCP idea is not valid for most protein pairs. This motivated a link prediction method based on paths of length three (L3) as a better representation of the topological patterns that emerge in protein networks. The results show the L3 method significantly outperforms other link prediction methods found in literature. Follow up studies showed that the L3 method can be further improved by considering a local community paradigm around each path of length three (CH-L3 method).

In this work we present a novel method for link prediction on complex networks based on continuous-time quantum walks. The control of a relative phase allows our method to be used in different types of networks (physical, social, biological, etc.). By exploiting quantum coherence we are able to outperform the state of the art classical methods, indicating that our method is also able to capture complex local patterns (such as local communities around paths of length three) without the need to impose a specific pattern structure. Our results indicate there is a strong potential for combining quantum algorithms with complex network research to produce tools with direct and immediate experimental relevance.

2.23 (BSCC) Raman spectroscopy of graphene and transition metal dichalcogenides for single photon emitters

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Transition metal dichalcogenides (TMDs) are a novel platform for quantum optics. TMDs are optically active, semiconducting layered materials in the form of MX2, with M being a transition metal atom, e.g. Mo, W,.. and X being a chalcogen atom, e.g. S, Se, or Te, which can be exfoliated from their bulk crystals down to monolayers. These layered materials (LMs) are promising for fast optoelectronics and on-chip photonics. We demonstrated the existence of quantum light emitters in atomically thin TMD layers [1-3]. These are obtained by micro-mechanical cleavage of bulk crystals and can be re-assembled to vertical heterostructures by stacking different LMs on top of each other. Raman spectroscopy is the primary tool to characterise graphene and related layered materials[4,5]. In combination with photoluminescence it is an essential characterisation technique to identify LMs and characterise the starting material and the final heterostructure used for single photon emission. I will introduce Raman spectroscopy of graphene and layered materials and explain how to use Raman spectroscopy it to identify the number of layers, doping, quality of the material. I will review the recent advances and outline its importance for characterising TMDs heterostructures used as platform for quantum optics.

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2.24 (BSCC) Optimization of Quantum Single-Electron Pumps

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Single-electron pumps are important for a wide range of quantum technologies, and they have been proposed as precise current sources for metrological purposes. The central goal is to transfer single electrons between two leads via a nano-scale island as accurately and as fast as possible. The gate voltages of the island are modulated periodically in time with the aim to generate a current given by the electron charge times the frequency of the drive.
In this contribution, we optimize the operation of single-electron charge pumps [1] and coherent single-electron emitters [2]. To this end, we evaluate the statistics of pumped charge on a wide range of driving frequencies using Floquet theory, focusing here on the current and the noise. For charge pumps controlled by one or two gate voltages, we demonstrate that our theoretical framework may lead to enhanced device performance. Specifically, by optimizing the driving parameters, we predict a significant increase in the frequencies for which a quantized current can be produced. For adiabatic two-parameter pumps and coherent single-electron emitters, we exploit that the pumped charge and the noise can be expressed as surface integrals over Berry curvatures in the parameter space. Our findings are important for the efforts to realize high-frequency charge pumping, and our predictions may be verified using current technology.
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2.25 (Computation) Deep Reinforcement Learning Based Control of Coherent Transport of Spin Qubits

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Several tasks involving the determination of the time evolution of a system of qubits require stochastic methods in order to identify the best sequence of gates and the time of interaction among the qubits. The major success of deep learning in several scientific disciplines has suggested its application to quantum information as well. Thanks to its capability to identify best strategy in those problems involving a competition between the short term and the long term rewards, deep reinforcement learning (DRL) [1] method has been successfully applied, for instance, to discover sequences of quantum gate operations minimizing the information loss. In order to extend the application of RL to the transfer of quantum information, we focus on Coherent Transport by Adiabatic Passage (CTAP) on a chain of semiconductor quantum dots (QD) [2], designed for instance to trasnfer qubits between distant location on a quantum chip [3]. This task is usually performed by the so called counter-intuitive sequence of gate pulses. Such sequence is capable of coherently transfer an electronic population from the first to the last site of an odd chain of QDs, by leaving the central QD unpopulated [4]. We apply a technique to find nearly optimal gate pulse sequence without explicitly give any prior knowledge of the underlying physical system to the DRL agent. Using the advantage actor-critic algorithm, with a small neural net as function approximator, we trained a DRL agent to choose the best action at every time step of the physical evolution to achieve the same results previously found only by ansatz solutions. We show that deep reinforcement learning can be employed to mitigate the non-ideality of practical quantum systems by suitably controlling their parameters during time evolution. More in general, such method can be applied to problems where an ansatz solution is unknown and to the real-time parameter correction of quantum systems.

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2.26 (Communication) Towards quantum state transfer between two ions separated by 400m

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An ion-based quantum interface is a promising building block for future quantum networks. The successful realization of entanglement swapping [1] and error correction [2] in an ion chain demonstrates the advantage of distributing long-distance quantum entanglement via an ion-based quantum repeater. In addition, compatibility with state-of-the-art quantum logic units based on ions makes an ionic quantum network an ideal choice for distributed quantum computation.

We are working on the experimental implementation of transferring an arbitrary quantum state between two distant ion-based quantum interfaces, which is an important step towards an ion-based quantum network. Here the two ionic quantum interfaces are located in two labs 400m apart, and the ion-photon interaction is enhanced by a high finesse cavity at each site. In this experiment, we will first convert the quantum state of ion 1 to a photonic state by means of a cavity-assisted Raman transition [3]. After transmission through a 400m fiber between two labs, the photonic qubit will be absorbed by ion 2, accomplishing the state transfer process. Furthermore, for higher photon mapping efficiency and fidelity, a heralded absorption scheme is discussed.

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2.27 (BSCC) Monte Carlo simulation of spin-blockade in CMOS-based qubits

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Qubits based on properly engineered silicon CMOS devices represent an interesting option for the implementation of a quantum computer using a widely available technology platform. In such qubits the information is encoded in the electron spin, therefore it is important to devise techniques suitable for spin readout.
We have thus developed a code for the detailed numerical simulation of single-electron circuits with an arbitrary number of islands, including both quantum confinement (in the constant interaction approximation) and spin-blockade effects.
We started from a Monte Carlo simulator for single-electron circuits that we have developed in the past, introducing, into the calculation of the energy variation associated with each possible transition through the tunnel junctions making up the circuit, the difference between the confinement energies of the states involved in the two dots. We can consider all possible transitions, i.e. between all pairs of filled-empty states, or just the most likely transitions (i.e. the ones involving only the states closest to the Fermi level), in order to reduce the computational burden. After reproducing the experimental data available in the literature for the behavior of a two-island structure, we have applied our code to the analysis of experiments performed on qubits in CMOS structures, computing the associated diamond diagrams characterized by the specific features that have been seen in recent experiments.
We also discuss our results in relationship with the implementation of spin detection (for qubit readout) based on the spin-blockade effect between neighboring islands.

2.28 (Computation) Optical Quantum Ultra Dense Parallel Information Processing

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We report on the logic capabilities and the physical limits of a novel non-conventional theoretical design towards quantum computing based on an ultradense parallel quantum information processing in chemically engineered supramolecular/nanodot arrays. The inputs and outputs are macroscopic, by multidimensional optical wave mixing using ultrafast lasers. Examples of implementations of the ultradense quantum information processing will be discussed based on the quantum dynamical response in different macroscopic phase matching directions of quantum dot arrays addressed by a sequence of fs laser pulses.[1-2] Preliminary experimental validation using 2D electronic spectroscopy of dimers in solution and on solid arrays at room temperature is available[3-4].
A molecule is not intrinsically a two level quantum system. We argue that in two essential ways a molecule is much more than a qubit or even coupled qubits. First, when suitably designed for particular ways of inputting the data a molecule is an N level system. We propose an approach that will enable us to encode $N2$ -1 logic variables on such an N level supramolecular system and process the $N2$ -1 logic variables in parallel. This dense processing is in contrast to purely classical logic that can only do N-1 operations. This superdense processing is made possible because, as first shown by Dirac (1927), the coherent quantum dynamics of an N level system requires $N2$-1 real valued variables for its characterization. These variables satisfy linearly coupled first order in time classical-mechanics-like equations of motion. The coefficients in these equations are determined by the optical pumping. Changing the parameters of the pumping such as the time intervals between pulses programs different logic computations.
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2.29 (BSCC) Active control of single photon sources using 2D materials

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Solid state quantum emitters are a mainstay of quantum nanophotonics as integrated single photon sources (SPS) and optical nanoprobes[1,2]. Integrating such emitters with active nanophotonic elements is desirable in order to attain efficient control of their optical properties but typically degrades the photostability of the emitter itself[2]. In our group, we have developped optomechanical[3] and optoelectrical[4] approaches to either tune energy and decay rate of single photon sources. In this talk, I will present recent experiments[4] that demonstrate a tuneable hybrid device which integrates lifetime-limited single emitters (linewidth 40 MHz) and 2D materials at sub-wavelength separation without degradation of the emission properties. Our device's nanoscale dimensions enable ultra-broadband tuning (tuning range $>$ 400 GHz) and fast modulation (frequency 100 MHz) of the emission energy, which renders it an integrated, ultra-compact tuneable SPS. Conversely, this offers a novel approach to optical sensing of 2D material properties using a single emitter as a nanoprobe. present a new type of hybrid system, consisting of an on-chip graphene NEMS suspended a few tens of nanometres above nitrogen-vacancy centres (NVCs), which are stable single-photon emitters embedded in nanodiamonds. *Work done in the framework of the 2D-SIPC quantum flagship project led by. Prof. Efetov, ICFO, Barcelona.*

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2.30 (BSCC) Photon Bubble instabilities

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Turbulent radiation flow is ubiquitous in many physical systems where light-matter interaction becomes relevant. Photon bubble instabilities, in particular, have been identified as a possible source of turbulent radiation transport in many astrophysical objects, such as massive stars and black hole accretion disks. Here, we report on the experimental observation of a photon bubble instability in cold atomic gases, in the presence of multiple scattering of light. Two different regimes are identified, namely the growth and formation of quasi-stationary structures of depleted atom density and increased photon number, akin to photon bubbles in astrophysical objects, and the destabilization of these structures in a second regime of photon bubble turbulence. A two-fluid theory is developed to model the coupled atom-photon gas and describe both the saturation of the instability in the regime of quasi-stationary bubbles and the low frequency turbulent phase associated with the growth and collapse of photon bubbles inside the atomic sample. We also employ statistical dimensionality reduction techniques to describe the low-dimensional nature of the turbulent regime and discuss the reconstruction of the phase space trajectories, together with the possible existence of chaos and/or strange attractors governing the system dynamics.

2.31 (Communication) Quantum advantage for probabilistic one-time programs

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One-time programs, computer programs which self-destruct after being run only once, are a powerful building block in cryptography and would allow for new forms of secure software distribution. However, ideal one-time programs have been proved to be unachievable using either classical or quantum resources. Here we relax the definition of one-time programs to allow some probability of error in the output and show that quantum mechanics offers security advantages over purely classical resources. We introduce a scheme for encoding probabilistic one-time programs as quantum states with prescribed measurement settings, explore their security, and experimentally demonstrate various one-time programs using measurements on single-photon states. These include classical logic gates, a program to solve Yao's millionaires problem, and a one-time delegation of a digital signature. By combining quantum and classical technology, we demonstrate that quantum techniques can enhance computing capabilities even before full-scale quantum computers are available.

2.32 (Communication) Photonic Integrated 2D material quantum components for future quantum networks

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Scalable IQNs will lead to technologies which will revolutionize the way we compute and communicate and will lead to new industries. IQNs will allow scalable quantum processors, quantum repeaters for extended secure quantum communication, as well as quantum sensing and metrology systems that use entanglement and squeezing to surpass classical devices. The key is to create, process, store, route and detect single photons. IQNs therefore require the integration of a variety of dedicated quantum devices, such as controllable SPEs, SPDs, switches and memories, which are assembled and connected in an array platform. The scalable integration of these quantum components into large scale IQNs, however remains to this date extremely challenging. While simple IQNs from free space coupled atomic networks cover entire laboratories, the recent development of chip based photonic IQNs created a lot of excitement in the field, as they seamlessly pave a way forward to the scaling up of IQNs. The challenge towards this goal however is the development, miniaturization, mutual compatibility and integration of the various quantum components onto existing photonics platforms. In particular, integration of SPEs into photonic cavities is still challenging. In addition, as these components are typically made from a variety of different materials and involve incompatible fabrication processes, their simultaneous integration proved to be extremely difficult and requires a concentrated material science and engineering effort. The recently discovered class of 2DMs can be assembled into entirely new types of vertical hetero-structures (HS), enabling previous impossible optoelectronic properties with bulk materials [Nature Nano. 10, 485 (2015)]. 2DMs cover almost every material class in condensed matter, e.g. semi-conductors, metals, semi-metals, superconductors, etc. [Nature 499, 419 (2013)]. As these 2DMs can be atomically engineered into vertical HSs, it is possible to combine and hybridize the functionalities of the different materials and to engineer band-gaps, emission spectra integrated on Si or SiN waveguides and enhance quantum effects. All 2DMs can be readily transferred into photonics networks in a scalable, non-invasive and mutually compatible way.

2.33 (Computation) A CMOS-compatible platform for multigate single-electron silicon devices

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Silicon is not only at the core of the vast majority of consumer-level integrated electronics, but is predicted to be an ideal building block for cutting edge technologies aiming to harness the quantum properties of individual electrons [1].
In this challenging field, there is growing need of full-stack fabrication solutions, able to incorporate carefully designed silicon nanostructures in conventional CMOS integrated circuits. Here we present a technological platform for the realization of flexible multigate single-electron silicon devices.

Our CMOS-compatible protocol allows the fabrication of highly-cristalline silicon-on-insulator (SOI) thin channels (down to 10 nm), which are gated by electrodes defined from two independent 50 nm-thick doped poly-silicon layers, embedded in high-quality silicon dioxide. Both the SOI channels and the gating elements are patterned with mix and match UV / electron-beam lithography, resulting in wafer-scale production with complete freedom of circuit design down to minimum lateral feature size of 30 nm.

Our platform yields customizable quantum devices which can be integrated on chip with a broad palette of technologies, also developed in-house. These include superconducting analog and digital circuits, silicon photonics, graphene and 2D materials, Micro-Electro-Mechanical Systems and Micro-Opto-Electro-Mechanical Systems.

This flexibility has recently been showcased in the first internal multi-project wafer fabrication run, where approximately 100 different designs have been jointly realized on 150 mm wafers, with applications ranging from quantum computation to single-electron sensing and pumping.
Morton et al. "Embracing the quantum limit in silicon computing" Nature 479, 345-353

2.34 (BSCC) How quantum are your many-body states? Towards scalable assessment of non-classicality in large many-body systems

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One of the tenets of future quantum technologies is the idea that many-body quantum superposition states can offer a fundamental improvement in accomplishing technological tasks - such as sensing, simulation and computing - when compared to states without quantum correlations. Therefore it is crucial to develop realistic and scalable strategies in order to assess the quantum nature of correlations in many-body states - and this is at first sight a formidable task, requiring in principle a (non-scalable) tomographic reconstruction.

In this presentation we shall discuss a sequence of theoretical and experimental strategies which can ascertain the quantum nature of large-scale, mixed many-body states in its various forms of increasing non-classicality, namely: quantum correlations at large; entanglement; EPR correlations; and Bell correlations. We will discuss how such criteria can be applied to many-body states in the vicinity of a quantum critical point, where critical quantum fluctuations lead to the strongest forms of quantum correlations known at equilibrium. Such states are readily accessible to quantum simulators for discrete variables (qubits encoded in trapped ions, Rydberg atoms, etc.) as well as continuous variables (lattice bosons). Making use of advanced numerics, we can reconstruct the "non-classicality phase diagram" (indicating the equilibrium regimes at finite temperature in which the various forms of quantum correlations can be detected) for paradigmatic models of quantum simulation, namely the quantum Ising model and the Bose-Hubbard model.

2.35 (BSCC) Enhancing Quantum Technology with RedCRAB Optimal Control

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Quantum optimal control theory solves problems by recasting them into a functional minimisation. Given an initial state vector, a dynamical law depending on external control fields, and a resulting figure of merit, the aim is to find the control fields that minimise the figure of merit. We have designed and implemented an optimisation algorithm that does not require the evaluation of a gradient. It can further be implemented in a closed-loop optimisation with minimal input requirements for the users [1]. The algorithm development was originally inspired by optimisation problems in many-body quantum physics simulations. The implementation is realised in a generic multi-purpose software suite called Remote Dressed Chopped Random Basis Optimisation Algorithm (RedCRAB). It consists of two key components: a server, where the actual optimisation algorithm is executed, and the client software that allows users to remotely interface their setups or simulations and perform the optimisation online. We are presenting applications of RedCRAB to a number of simulations and experiments on various physical platforms.

Together with Bruker Biospin, a leading company in Magnetic Resonance instrumentation, we are directly optimising certain NMR and EPR experiments to improve their service performance. In contrast to other optimisation methods in their field, our method works even if the system is subject to unexpected sources of noise. RedCRAB is also used in a collaborative project with Harvard University to optimally prepare different many-body quantum states of Rydberg atoms in optical lattices. In experiments with nitrogen-vacancy colour centre, RedCRAB is being integrated in the existing control software "QUDI" [2] to improve the performance of quantum sensing at room temperature. General multi-qubit gate optimisations are also being carried out together with the Hebrew University of Jerusalem. This number of applications shows the promising potential of RedCRAB in significantly increasing the performance of quantum technology by finding optimal and robust controls and parameters that can not be reached without quantum optimal control.

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2.36 (Communication) Optimizing QKD backbones to secure large optical transport networks

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Quantum Key Distribution (QKD) is the first and by far the most technologically ready application of Quantum Communications technologies to telecommunication networks. In essence, QKD devices and protocols exploit a number of "quirks" of quantum mechanics to achieve the continuous exchange of a random bit stream between two communicating parties, with an arbitrarily low upper bound on the probability that an adversary eavesdropped the communication, making it an ideal choice to generate key material for cryptography (especially session keys). Despite the security guarantees, several practical limitations still prevent the widespread adoption of QKD, among them: communication is largely still point-to-point, practical reach in fibers is limited to about one hundred kilometers, low key rate, lack of authentication in QKD protocols, high cost of the devices and complex deployment. Irrespective of all these limitations, QKD-based products are finally close to commercial deployment in core transport networks, thus making the investigation of their optimal employment a relevant problem.

In this work we propose a MILP formulation for finding the optimal (i.e., cheapest) placement of QKD devices to create a QKD backbone for securing an existing foptical transport network, with a desired level of path redundancy; we will show that significant savings can be achieved in multipath scenarios.

2.37 (Communication) Sequential Time-Bin Entanglement using SiN Microring Resonator Photon-Pair Sources

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Photonic sources represent a key building block for quantum communication. As systems move towards more complex quantum networks or more practical, low-cost, schemes, integrated photonics will play an important role. In the case of photon pairs, the platform of choice has been silicon (Si) due to the mature Si-Photonics technology. However, Si suffers from linear and nonlinear losses, such as Two Photon Absorption (TPA), which limits the achievable photon-pair generation rates in such devices. An alternative solution is silicon nitride (SiN), which does not suffer from TPA and where significant progress has been made in fabrication techniques as well as loss reduction. To demonstrate the maturity and flexibility of this technology we exploit SiN microring-resonators (MRR) in an entanglement generation scheme to realise sequential time-bin entanglement. In our experiment, sequential time-bin entanglement is investigated using a folded Franson interferometer setup giving rise to interference fringes with raw visibility up to 98%. The free spectral range of the MRR is adapted to match the standard telecom C-band channel spacing, thus permitting us to exploit low loss commercial telecom filters. This, together with photon detection using state of the art superconducting single photon detectors that we have developed, permitted us to detect coincidence counts of up to 80 kHz with further room for improvement. A MRR device with a moderate Q-factor ($2x10\hat{}5$) was chosen to allow us to operate with a 750 MHz pulsed pump rate. We also present several techniques that we have incorporated to characterise and mitigate noise while improving pump rejection and channel selection.

2.38 (BSCC) Multiplexed quantum memory for generation and processing of single photons via spatially-resolved detection

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In a recent experiment performed in our group we demonstrated the ability to generate on-demand single photons using a cold atom quantum memory [1]. The photons originating from a laser-cooled atoms held in a magnetooptical trap (MOT) are an ideal candidate for implementation of a quantum repeater protocol - an essential component of a quantum communications network. By introducing the multiplexing of angular emission modes we effectively create a highly multimode source of quantum light. We are able to multiplex at least 600 independent modes and store atomic excitations for over 50 μs. The memory feature enables real-time feedback, that could lead to a nearly-deterministic single-photon source [1]. The setup operates thanks to a single-photon sensitive camera based on an image intensifier. With the development of a FPGA-based feedback from an ultrafast sensor, the way stands open towards a train of true single photons.

Most recently we also learned to manipulate single photons stored as spin waves in our quantum memory, which could be a way to realize simple quantum processing protocols within the linear-optical scheme. In particular, by spin-wave diffraction-based beamsplitter realized using a periodic ac-Stark modulation [2] we performed Hong-Ou-Mandel interference of heralded single spin waves [3]. The system operates by generating light patterns in a feedback algorithm, achieving unprecedented control over spatial light intensity with prospects of improvement given by new coherence control techniques.

The new spin-wave processing schemes equips quantum repeaters with basic quantum information processing capability. In such a way the memory could serve as a quantum error correction coprocessor integrated in a repeater-based network. The ac-Stark modulation technique also extends the capabilities of the Gradient Echo Memory, allowing both parallelized processing and storage.

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2.39 (BSCC) Photonic Like Cooper Pairs

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When propagating in a material, photon pairs may effectively interact and exchange energy. For example, in Raman processes, an incident photon is converted into a lower frequency one, the remaining energy generating a vibration of the illuminated material, known as a Stokes process. Another possibility is that the incoming photon absorbs a vibration and is converted into a blue-shifted (anti-Stokes) one. Sometimes, these processes can combine into a single scattering event in which the vibration created by a Stokes conversion is the one that generates an anti-Stokes photon. While such a combined Stokes–anti-Stokes process is often obfuscated by the usual single scattering mechanisms, this second-order effect dominates the anti-Stokes production in the absence of thermal vibrations. In this case, both events can be understood as a single energy preserving scattering process in which two incoming photons of frequency ωL effectively interact through the medium to generate a pair of outcoming photons, one red (ωS) and one blue(ωaS)-shifted from the incident light, such that 2ωL=ωS+ωaS. This phenomenon has been observed in materials as diverse as diamond and water, and should be present as long as Raman resonances are available.
In this work we demonstrate theoretically and experimentally that photon pairs may also interact via a virtual vibration, meaning that the energy exchanged in the process is outside the spectral energy range of normal vibrations in the medium. In this case, the interaction is mediated by the vacuum of the quantized vibrational degree of freedom and the outuput field is composed of twin photons of different tunable frequencies.
The same process occurs for electrons in a metal at very low temperatures, where virtual vibrations of the medium attractively couple them, forming the so-called Cooper pairs. In fact, the Hamiltonian derived in our work is the bosonic counterpart of the standard BSC Hamiltonian in the mean field approximation. For electrons, this phenomenon changes a normal metal into a superconductor. Cooper pairs are the supercurrent carriers and we have shown here their photonic counterparts. Whether this analogy can be ex- tended to a photonic equivalent of superconductivity is a challenging and intriguing question for future investigation.

2.40 (Simulation) Self-bound states in Bose-Einstein condensates: From incoherent mixtures to coherent coupling

Julio Sanz [1], Cesar Cabrera [1], Anika Frölian [1], Craig Chisholm [1], Philip Thomas [1], Bruno Naylor [1], Luca Tanzi [1], Pierrick Cheiney [1], Leticia Tarruell [1]

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Self-bound states appear in contexts as diverse as solitary waves in channels, optical solitons in non-linear media and liquid droplets. Their binding results from a balance between attractive forces, which tend to make the system collapse, and repulsive ones, which stabilize it to a finite size. In my poster, I will present experiments on various self-bound states possible in two-component Bose-Einstein condensates with tunable interactions.
First, I will discuss the stabilization of dilute quantum liquid droplets: macroscopic clusters of ultra-cold atoms that are eight orders of magnitude more dilute than liquid Helium, but have similar liquid-like properties. In particular, they remain self-trapped in the absence of external confinement due to the compensation of attractive mean-field forces and an effective repulsion stemming from quantum fluctuations [1]. We observe that for small atom numbers quantum pressure is sufficient to dissociate the droplets and drive a liquid-to-gas transition, which we map out as a function of atom number and interaction strength [2].

In a second series of experiments, we study the difference existing between these liquid droplets and two-component bright solitons. In analogy to non-linear optics, the former can be seen as one-dimensional matter-wave solitons stabilized by dispersion, whereas the latter correspond to high-dimensional solitons stabilized by a higher order non-linearity due to quantum fluctuations. We find that depending on the system parameters, solitons and droplets can be smoothly connected or remain distinct states coexisting only in a bi-stable region [3].

Finally, we explore the scattering properties of a coherent superposition of two Bose-Einstein condensates with very unequal interactions. By adjusting the composition of the system, we observe as well the formation of self-bound states in this system, and study their properties.

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2.41 (Sensing) Lasing from cold strontium atoms with strong collective coupling

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Highly concentrated efforts to improve the performance of optical atomic clocks, have resulted in an unprecedented fractional frequency uncertainty of low 10ˆ-18[1] and a stability below the 10ˆ-19level [1,2]. This level of stability demands long integration times, in order to average down the limiting noise of the reference oscillator. Reducing the oscillator noise can thus directly improve the performance of current state-of-the-art optical atomic clocks.
This has sparked interest in the development of alternative approaches to realizing ultra low noise references. One such approach is the promising concept of active optical clocks where narrow-linewidth light is emitted directly on a forbidden atomic transition [3, 4]. This allows the realization of a laser source that is inherently narrow as well as accurate. By using forbidden optical atomic transitions in an optical cavity, strong collective coupling can be exploited to generate coherent emission of light. Placing the system in the fast cavity regime where the cavity decay rate is much faster than the atomic decay rate, $>>$, the cavity noise can be severely suppressed. The thermal noise in the cavity is currently the limiting factor in ultra stable reference cavities [5].
Here we present current progress in the the realization of an active narrow-line atomic reference using a thermal ensemble of cooled 88Sr atoms on the 3P1→ 1S0 intercombination line. We present a model including a broad range of dynamical behaviours of the atoms. We observe pulses lasting few microseconds in the cavity mode, and measure the characteristic dynamics of the emitted light. We evaluate the pulse shape dependency on cavity detuning, and map out photon flux dependencies on the number of atoms in the cavity mode. The system is modeled and experiments are compared to simulations, allowing new insight into the quantitative behavior of a non-ideal atomic sample.

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2.42 (Simulation) Quantum principles for neural information processing for diagnosis and rehabilitation in PTSD

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We present principles of quantum machine learning applied for neural diagnosis and recovery. Proposed is the formulation for neural diagnosis of event related spikes and potentials for electronencaphalography EEG data. We use the Muse headband to aggregate EEG data corresponding to neural spikes for a single rest state activity. The four channel data in the muse headband is recorder in the form of spikes corresponding to neural activation. In the normal case, these spikes are limited to muscle activity and related movement(s). In case of Post traumatic stress disorders (PTSD), these spikes in filtered EEG data correspond to hallucinations in the auditory and occipital cortex. We intend to isolate such spikes using global optimization techniques in the quantum annealing sense. We present the Ising formulation for quantum annealing and localize spikes in EEG data based on global optima. The Ising annealing allows us to explore nonconvex frontiers of response surface data for abnormal activity, hence yielding a global optimum. If the difference in spike heights for EEG data exceeds a predfined threshold, we identify it as PTSD. A host of other quantum machine learning techniques such as Grover's search are explored to identify PTSD accurately. We then propose a rehabilitation mechanism in the form of Virtual Reality devices to identify point of recovery for PTSD. This yields an interative loop in the form of diagnoses on the DWAVE system using Ising Annealing and neurotherapeutive feedback from virtual reality devices in the form of a warfare gaming environment. We then extend the quantum machine learning framework to other neurological disorders such as dementia and schizophrenia. We achieve excellent source localization for PTSD using quantum machine learning within tolerance of a few percent of accuracy. The neuro feedback mechanism gives us a sustainable score for measuring neural recovery from neurological disorders and helps establish the point of recovery for PTSD. Our studies have strong promise in the applied neurlogical information processing fields & the required apparatus for an extensible framework for diagnosis and treatment of post traumatic stress disorder.

2.43 (Computation) Effective Hamiltonian theory of the geometric evolution of quantum systems

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We present an effective Hamiltonian description of the quantum dynamics of a generalized Lambda system undergoing adiabatic evolution [1]. We assume the system to be initialized in the dark subspace and show that its holonomic evolution can be viewed as a conventional Hamiltonian dynamics in an appropriately chosen extended Hilbert space. In contrast to the existing approaches, our method does not require the calculation of the non-Abelian Berry connection and can be applied without any parametrization of the dark subspace, which becomes a challenging problem with increasing system size.

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2.44 (Computation) Josephson parametric amplifiers fabricated in wafer-scale with side-wall passivated spacer junction technology

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VTT's superconducting fabrication lines have been and are used for a variety of applications including sensors, electronics, and qubit structures. In this presentation, we describe our Josephson parametric amplifier (JPA) for a frequency band around 600 MHz [1], enabled by our side-wall passivated spacer (SWAPS) niobium process for Josephson junctions [2]. JPAs are low-noise superconducting amplifiers capable of going near the quantum limit of added noise and sometimes even below. Compared to high electron mobility transistor-based amplifiers, JPAs permit the use of novel techniques, for example, in the search for dark-matter particles or in the readout of qubits in quantum information systems.

We will review recent work on our JPA based on lumped-element series arrays of superconducting quantum interference devices (SQUIDs). We will cover points such as operation of the device with flux pumping as well as its properties including a low noise temperature of 105 mK and a maximum input signal power of -120 dBm. The device has been employed in recent nanobolometer experiments [3], allowing a record-low noise-equivalent power of 2 × 10ˆ{-20} W/$\sqrt{}$Hz. Further plans for the JPA include detection of single electrons with radio-frequency single-electron transistors, single photons with nanocalorimeters [4], and RF-reflectometry of charge qubits [5]. We will augment our presentation with some preliminary data from our improved sub-GHz JPA with an expected bandwidth of 2 MHz at 20 dB gain, a ten-fold increase over the past device generation. With the SWAPS process, our future focus will be on traveling wave parametric amplifiers (TWPAs). We will make a brief comment on their expected performance.

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2.45 (BSCC) Observing the transition from quantum to classical energy correlations with photon pairs

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The exact role of entanglement in various quantum metrology schemes is still subject to debates. This is why it is interesting to be able to experimentally control the relative amount of quantum and classical correlations. Here, we propose and experimentally realize a scheme to control the transition from quantum to classical correlations with energy correlated photons. A characteristic of entangled photon pairs is to show very strong energy correlations, together with strong temporal correlations. By introducing random phases on their spectral components and measuring the temporal shape of the two-photon wavefunction, we observe a diverging temporal second-order correlation function that is explained by a mixture between an energy entangled pure state and a fully classically correlated mixed state. The process is fundamentally non-unitary. The possibility to control the amount of classical versus quantum energy correlations will be an essential tool to experimentally verify the fundamental advantage of entangled states against classical correlations in any setup relying on time-energy measurements, for instance as in quantum spectroscopy schemes.

2.46 (Communication) Silicon Nitride Integrated Photonic Circuits for Quantum Operations

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Quantum optics provided a basis for a variety of scientific and technological advancements throughout last decades in areas ranging from extremely sensitive metrology to high-performance computing and secure communications. Quantum systems could be built based on different phenomena and use different information carriers, but photonics occupies a special place among other realizations due to the possibility to incorporate quantum states generation, transmission and measurements on a single platform having less sensitivity to environmental noise. The ability to transfer required functional parts on photonic integrated chips is unavoidable step towards moving those technologies from research centers to real world applications.
At LIGENTEC, we are offering an all-nitride-core based platform for quantum applications and succeed in achieving several crucial milestones, which bring us now closer to a bright quantum future: a variety of functional elements (delay lines, MMI, MZI, etc.) for large-scale integrated systems can be realised on chip while maintaining ultra-low propagation (< 0.1 dB/cm) and bend (< 0.001 dB/bend) losses, having small footprint and high stability. I/O-couplers adapted for most common fibers were specially developed to make communication with "the outside world" more efficient. The possibility of dispersion engineering and proven realization of microring resonators with Q-factors up to 15 million [1] and small bend radii open new prospects for quantum operations: they provide opportunities for photon-pair generation via Spontaneous Four Wave Mixing (SFWM) [2], while the resonators' narrow bandwidth and possible tunability could provide high degree of in-distinguishability of generated photons in different experimental schemes. Furthermore, Silicon Nitride itself allows power levels of operation to be high due to the absence of Two-Photon Absorption (TPA) [3]. To date, integrated photonics took its solid ground in applications such as Quantum Key Distribution [4], Random Number Generation [5] and others. We are going to share mentioned and other benefits of Silicon Nitride integrated photonic circuits for quantum and opportunities that it brings to research and industry.

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2.47 (BSCC) Entangled two-photon absorption cross-section of Rhodamine 6G.

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The two-photon absorption is a well-studied process, also well-known for its quadratic dependence of the absorption rate on the input flux, and thus for its inefficiency – typical two-photon absorption cross-section values for different materials are about 10–50 cm4 s photon–1, requiring high power laser pulses to compensate it. It automatically excludes samples with the low damage threshold from consideration.
Recently developed theory of entangled two-photon absorption (ETPA) predicts linear dependence of an entangled pairs absorption rate on the pairs flux in the low-power regime, and provides a tool to overcome this obstacle – linear process is obviously more efficient than quadratic, thou implying detection difficulties. To show this signature, the ETPA induced fluorescence intensity of Rh6G ethanol solution was measured as a function of 1064 nm SPDC Type-0 pairs flux and Rh6G concentration, and corresponding Rh6G ETPA cross-sections for the mentioned wavelength were first obtained.
The developed methods have possible applications in sensing and spectroscopy, especially for biological objects *in vivo*, due to absence of any possible damage for the typical SPDC fluxes.

2.48 (Communication) POVM-Based Quantum Random Number Generator

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Random numbers are a fundamental resource in science and engineering with critical applications in cryptography. The widely used pseudo random number generator (RNG) and True RNG can not certify the randomness of their output, since they rely on a deterministic algorithm or classical processes. In contrast, a quantum random number generator (QRNG) generates genuine randomness from the intrinsic probabilistic nature of quantum mechanics. The existing QRNG protocols can be mainly classified into three different categories: the trusted (high speed, low security), device-independent (low speed, high security) and semi-device-independent (good generation rates with minor assumptions) QRNGs. To balance the performance and the security, the semi-DI-QRNG provides a trade-off between the practical and device independent QRNGs, where high speed and low cost informational provable randomness can be generated under several reasonable assumptions without requiring trusted and complete model assumptions on devices. In this work we describe the theory and experimental details of positive-operator valued measure (POVM) based QRNG. We exploit this idea for finite dimensional Hilbert spaces and arbitrary numbers of POVMs. Particularly, we start analyzing the case of three, four and six state POVMs, then derive a bound for an arbitrary number of POVMs with fixed dimension. The amount of extractable random bits is estimated by optimizing the conditional min-entropy, which is lower bounded based on experimental data and few general assumptions. We express the optimization problem into an Semi-Definite Program (SDP) which can be efficiently solved by computers. In the derivation of the bounds we consider both trusted and semi-DI scenarios. Finally we performed several statistical tests such as NIST test, on the generated numbers, all the tests were passed.

2.49 (Communication) Bragg-reflection waveguides as photon pair sources for polymer photonic circuits

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Recent advances in quantum technology enable increasingly complex quantum communication and information experiments. However, many implementations of quantum systems still suffer from their large size, high cost, and limited availability. As part of the UNIQORN project, we have been tasked to develop a compact and low-cost semiconductor source of photon pairs in the telecom wavelength range which will be integrated into versatile polymer photonic circuits. To achieve this, we adapt and optimize our Bragg-reflection waveguides (BRWs) towards efficient coupling to the polymer waveguides and for direct electrically pumped generation of photon pairs via parametric down-conversion (PDC).

In this work, we characterize such a BRW made from AlGaAs, which features an AlGaInAs quantum dot layer surrounded by quantum wells as gain media for an internal laser. By pumping the waveguide optically using a telecom laser, we explore the transmission properties and second harmonic generation (SHG) performance of our structures. To enable PDC, the phase-matching condition needs to be fulfilled; consequently the quantum dot laser spectrum needs to overlap with the SHG wavelength. Therefore, we electrically contact the sample and investigate the dependence of the lasing spectrum on the applied voltage and the sample temperature.

Ultimately, the optimization of these electrically pumped samples and their integration into polymer networks will allow us to establish bright, on-chip sources of time-bin or polarization entangled photon pairs in the telecom wavelength range working around room temperature.

2.50 (BSCC) Efficient generation of sub-Poissonian light via coherent diffusive photonics

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Quantum states of light possess capabilities exceeding those of classical light. Although non-classical states with well-defined photon number find many applications in quantum information processing [1-4], methods for their deterministic and efficient generation remain elusive. In this work we numerically demonstrate the viability of non-linear coupled waveguides for deterministic generation of sub-Poissonian states - possessing a sharp photon number distribution - and for exploration of the interplay between Hermitian and non-Hermitian (diffusive) dynamics. It is known, for example, that diffusive coupling between can lead to rich quantum properties such as entanglement generation [5], protection against decoherence [6], or single-photon generation [7].

We simulate a system of two bosonic "signal" modes in the waveguides, which are diffusively coupled via a long "tail" of evanescently coupled waveguides acting as a reservoir. All modes are subject to a strong χ^3 nonlinearity. We demonstrate evolution of an input coherent state to a sub-Poissonian output (Mandel parameter $Q < 0$) via an effective interaction mediated by the nonlinearity. The input state evolves to a sub-Poissonian output in the superposition basis of signal modes, over timescales inversely proportional to the input amplitude. We also observe entanglement generation in the original basis of signal modes. Over short timescales the tail of waveguides approximates a Markovian reservoir, allowing our system to reproduce the output of theory [7]. Our system can be readily fabricated in photonic waveguides [8] and so with experiment in focus we use our simulations to explore the optimal regimes for coupling strengths and propagation length, with the ultimate aim to provide a deterministic and compact source of sub-Poissonian light.

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2.51 (Sensing) Tunneling-based Molecular Sensing Using Nanoscale Devices

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Quantum tunneling of charge carriers is a powerful platform for sensing (bio-) molecules from the liquid or gas phase. I will review our recent investigations on the tunneling charge transport through molecular films of nanometer thickness, which sensitively depends on the electronic structure of the molecules, the degree of order in the film and the nature of the organic-inorganic interface to the contacts. Our transport measurements made on alkylphosphonate self-assembled monolayers reveal distinct contributions from non-resonant "through-bond", trap-assisted and "through-space" tunneling [1,2]. We have fabricated silicon contacts separated by 4 nm distance to investigate the charge transport through proteins. At low-temperatures, the measured conductance through cytochrome c is in agreement with tunneling through the formed silicon-protein-silicon junction [3].

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2.52 (Computation) Tetrapartite entanglement measurements of W-Class in noninertial frames

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We present the entanglement measures of a tetrapartite W-Class entangled system in noninertial frame, where the transformation between Minkowski and Rindler coordinates is applied. Two cases are considered. First, when one qubit has uniform acceleration whilst the other three remain stationary. Second, when two qubits have nonuniform accelerations and the others stay inertial. The 1 - 1 tangle, 1 - 3 tangle and whole entanglement measurements, are studied and illustrated with graphics through their dependency on the acceleration parameter rd for the first case and rc and rd for the second case. It is found that the Negativities and pi-tangle decrease when the acceleration parameter rd or in the second case rc and rd increase, remaining a nonzero entanglement in the majority of the results. This means that the system will be always entangled except for special cases. It is shown that only the 1-1 tangle for the first case, vanishes at infinite accelerations, but for the second case the 1 -1 tangle disappears completely in this limit. It is found an analytical expression for von Neumann information entropy of the system and we notice that it increases with the acceleration parameter.

2.53 (Communication) Experimental Schemes for Improved Continuous Variable Quantum Cryptography

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Continuous Variable Quantum Key Distribution (CVQKD) [1,2]is a promising alternative to Discrete-Variable (DV) QKD, offering the major advantage to be compatible with coherent optical communication systems, which are the current standard technology for metro and long haul optical networking. CVQKD also has a strong potential for implementation with cost-effective devices by allowing for chip-level integration, using for instance silicon photonics technology. European research and development in these directions are supported by the flagship project CIVIQ (Continuous Variable Quantum Communications) that has started in October 2018, with 21 industrial and academic partners. In this poster we will present our ongoing work within CIVIQ, with two main goals:
(i) starting from previous practical CVQKD demonstrations [3,4,5]using lab-standard devices, move towards industry-standard devices, by increasing the pulse rate from the MHz to the GHz range, by using independent lasers for the signal (on the emitter side) and local oscillator (on the receiver side), and by exploiting up-to-date digital signal processing (DSP) for phase and polarization recovery. This work is done in collaboration with Nokia Bell Labs France, which has recognized expertise on high-rate optical coherent telecommunication systems [6].
(ii) integrating the main parts of a CVQKD device on silicon photonics chips, including in particular on-chip phase and amplitude modulators, homodyne or heterodyne detection (using 90$\circ$ hybrids), and photodetectors (using Germanium on Silicon technology). We will present current performances, allowing for secret key distribution for typical distances of up to 50 km. This work is done in collaboration with the C2N lab in Palaiseau, France, which has a long experience in designing and testing silicon photonics components [7].
In addition, various open issues related to CVQKD security proofs and practical network implementations will be discussed.

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2.54 (Communication) Compensation of side channels in continuous-variable quantum key distribution

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Continuous-variable quantum key distribution (CV QKD) is aimed at highly efficient realization of quantum cryptography using accessible components for optical communications. However, its practical realization substantially depends on imperfections of the realistic devices. It is therefore important to analyse the role of side channels, which are partially accessible to an eavesdropper, in security of CV QKD and suggest methods aimed at compensation of side channels in practical CV QKD. While some of the side channels, concerned with detector imperfections, can be ruled out using measurement-device-independent CV QKD, such schemes demonstrate higher sensitivity to channel loss compared to conventional CV QKD protocols. We therefore study how the side channels can be taken into account and possibly compensated for in the framework of standard device-dependent CV QKD protocols using coherent or squeezed states of light. We consider side channel loss on the preparation side of CV QKD protocols and side-channel noise infusion on the detection side of the scheme. We show how sender-side leakage after the modulation stage can be potentially compensated for by controllable addition of noise to the side-channel input. As for the leakage prior to detection, it constitutes a threat only to squeezed signals and can be compensated for by infusion of respectively squeezed states to the side-channel input. Furthermore, we consider excessive modulation applied to auxiliary modes and directly leaking to an eavesdropper, which appears to be more threatening for squeezed-state protocols and may require optimization of squeezing. On the detection side we show how monitoring on the residual noise from the side-channel noise infusion can be helpful for compensating the negative impact of the respective side channel. Our results show the pathway towards highly efficient QKD secure against potential practical imperfections.

2.55 (Computation) High-finesse tunable cavity on a closed-cycle cryostat

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The light-matter interactions in a solid-state based quantum emitter combined with an optical cavity is a vital tool for realization of quantum technologies, as well as fundamental studies in the field of cavity quantum electrodynamics. A promising platform has emerged based on Fabry-Perot cavity combined with capability for spectral and spatial tuning, which enables tuning cavity resonance for effective photon confinement and interaction with individual quantum emitter over large areas [1 - 3]. We will show our recent progress towards achieving high-finesse stable cavity at low temperature in a closed-cycle cryostat integrated with an optical table. We will discuss various aspects of setup, particularly mechanical stability and show recent measurements characterizing the performance of the setup.

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2.56 (Simulation) Probing dynamics in quantum magnetism with ultracold atoms

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We consider time-dependent dynamics in magnetic models corresponding to two-component bosons in an optical lattice. Beginning from a state with all effective magnetic spins in the same direction, we investigate dynamics of spin-spin correlations, and how they behave in situations with different interaction ranges and for different total spin. We show in some cases that this leads to synchronisation between the spins. One of the challenges in working with these systems in the laboratory remains reaching the low temperatures/entropies necessary to produce some particularly sensitive interacting states, and rotating the spins adiabatically from a low-entropy initial state provides a promising route to lower temperature many-body states.

2.57 (Computation) Quantum Theoretical study of hexagonal ice: ab initio electronic structures & IR spectra

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The ice crystals developed in the cirrus clouds have been investigated experimentally during the past century. These ice crystals generated at low temperatures have acquired forms like cubic and hexagonal ice crystals (1,2), dendritic ice crystals, pentagonal and hexagonal prisms, roughened hexagonal ice aggregates, pristine hexagonal ice columns , rosettes (four-branched) , plates, needles... like main geometries observed in in cirrus, and polar stratospheric clouds. As well, theoretical investigations have been conducted applying first-principles quantum mechanical calculations on these ice crystals have been carried out to find their geometries, harmonic and anharmonic vibrational energies, and their relative stabilities (3-5).
In order to know the electronic structures of ice crystals -mainly the hexagonal ice prisms- was used the Density Functional Theory considering the hybrid method B3LYP with the aug-cc-pVTZ Dunning's Basis set like a high level of theory. Several initial electronic structures have been optimized starting from (H2O)n, $n = 6 - 18$. The initial ζ-matrixes were generated with six H2O molecules to reach the *ab initio* hexagonal-water geometry optimized adding six H2O molecules successively. The Infrared spectra were obtained to assess others physico-chemical properties for each electronic structure achieved.

The preliminary results offer the hexagonal ice crystal geometries in correspondence with experimental data like hexagonal ice plates and prisms. These outcomes can be considered as incipient ice geometries to explain the snow crystals like the four-branched bullet rosettes. The spectra help to elucidate the hydrogen bonds on each hexagonal ice crystal geometry, the vibrational motions as the internal parameters like distances, angles. These results are useful for experimentalists to know the scattering properties of cirrus clouds as well as their optical properties of ice crystals.

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2.58 (BSCC) Superconducting circuits in silicon technology

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We aim to construct a superconducting qubit using only scalable manufacturing techniques, to contribute to the mass-producibility of quantum computers. In the gatemon qubit design, the energy level spacing is tuned by applying a gate voltage to the weak link that connects the bit to superconducting reservoirs. Currently a nanowire is used for this link [1], which is hard to fabricate in a reproducible and scalable manner. We aim to replace this by a regular MOSFET (Metal Oxide Semiconductor Field Effect Transistor) [2], which is readily integrable into standard CMOS processes. To this purpose, the source and drain contacts of the transistor need to be made of superconducting material, and the design needs to be adapted such that the proximity-induced superconductivity in the channel is strong enough to observe the Josephson effect. Our current focus is on studying the fabrication process and superconducting properties of three silicides (CoSi2, PtSi and V3Si) and highly boron-doped silicon (Si:B) to be used for the contacts, which due to their silicon content are likely to provide a good interface to the channel.

2.59 (Simulation) Implementing quantum stochastic differential equations on a quantum computer

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We study how to implement quantum stochastic differential equations (QSDEs) on a quantum computer. This is illustrated by an implementation of the QSDE that couples a laser driven two-level atom to the electromagnetic field in the vacuum state on the IBMqx4 Tenerife computer. We compare the resulting master equation and quantum filtering equations to existing theory. In this way we characterize the performance of the computer.

2.60 (Computation) High-fidelity quantum control and quantum information processing with composite pulses

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[3] Bulgarian Academy of Sciences – Bulgaria

The technique of composite pulses replaces the single pulse used traditionally for driving a qubit by a sequence of pulses with suitably chosen phases, which are used as control parameters for shaping the excitation profile in a desired manner. Composite pulses produce unitary operations, which combine very high fidelity with robustness to parameter variations. We have developed a pool of composite pulses by using a novel SU(2) approach and have designed recipes for construction of single-qubit operations, including broadband, narrowband and passband pulses for complete population inversion, phase and rotation gates, universal composite pulses, composite adiabatic passage and composite STIRAP [1-4], some of which have already been demonstrated in experiments with doped solids and trapped ions. We have also designed efficient and robust composite techniques for construction of highly entangled states, e.g. Dicke and NOON states, and multi-qubit gates, e.g. C-phase, Toffoli, and generally CN-phase gates. Recently, high-fidelity methods for dynamical decoupling based on similar ideas have been designed and experimentally demonstrated [5].

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2.61 (BSCC) Quantum measurement and control of levitated nano-particles

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Considerable developments are being made in controlling quantum systems through a combination of measurement and feedback. By appropriately interpreting the measurement information and characterising the resulting disturbance, we can determine how to perform feedback in such a way as to drive the system into low-temperature and potentially highly non-classical states [1].
We have been interested specifically in using feedback to prepare and manipulate quantum states of motion of levitated nano-particles. Strong permanent magnets have been shown capable of producing sufficiently large trapping potentials for levitated particles about a micron in diameter [2]. This parameter regime differs from previous work with trapped ions or other nano-mechanical resonators in high-frequency trap systems. In particular, to outpace environmental heating these systems typically need to be controlled on a time-scale comparable to the trap frequency. This poses an interesting challenge, for which we have developed a theoretical framework for preparing motional states with visible quantum properties.

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2.62 (Sensing) Quantum Ghost Imaging for Remote Sensing and 3D-Imaging

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Modern imaging systems in biology and medicine as well as recording techniques for security and catastrophe scenarios are generating a growing demand for imaging techniques capable of returning high-resolution images through scattering and turbulent media.
For these scenarios IR wavelengths are ideal as they have good atmospheric transmission properties and low scattering cross-section. However, the detection of backscattered photons requires dedicated, ultrafast, highly sensitive sensors, while matured silicon technology is not utilizable at IR wavelengths.

By exploiting the correlation of entangled photon pairs in quantum ghost imaging setups, it is possible to obtain the information and the registration of the image in different parts of the spectrum. Therefore, ideal wavelengths for object illumination (i.e. maximum penetration depth, IR) and imaging (maximum detector efficiency, VIS) can be used at the same time.

An additional advantage of the quantum correlation is the possibility of filtering classical noise by coincidence detection of photon pairs, therefore obtaining virtually noise-free images.

Current setups for quantum ghost imaging use a single pixel heralding detector in one arm to trigger a spatially resolving imaging detector in the other arm. This heralding scheme needs prior information on distances to setup appropriate delay lines while only returning 2D information. For remote sensing over large distances, these delay lines are not feasible.
We propose a setup for quantum ghost imaging suitable for both remote sensing and 3D imaging by replacing the camera and optical delay line with a photon timing camera and subsequent coincidence detection via an intelligent photon-pair matching algorithm.

2.63 (Simulation) Dephasing and relaxation of topological states in extended quantum Ising models

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We study the decoherence and the relaxation dynamics of topological states in an extended class of quantum Ising chains which can present a manyfold ground state subspace. In order to understand the robustness of the topological properties of these spin chains in presence of realistic dissipative interaction, we assume that each spin is affected by a dephasing interaction with a local bath. By deriving the Lindblad equation using the many-body states, we investigate the relation between the decoherence, the energy relaxation and the topology.The extended models have higher topologically numbers in the topological phase, characterized by a manyfold ground state subspace, with several Majorana modes. We derive formulas for the decoherence and relaxation rates which are related to generalized overlaps of wave functions involving several Majorana zero modes. This generalized overlap factor still decreases exponentially with the length of the chain. As a result the ground state subspace is suitable to encode information on exponentially long time scale.

2.64 (Sensing) Design of optomechanical resonators for micro-scaled quantum thermomethers based in diamonds

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A new EMPIR Project (17FUN05) devoted to the research in photonic and quantum optomechanic devices for temperature measurements at micro and nanoscale was launched in 2018. This project aims at exploring the potential of high resolution photonics and optomechanical sensors in terms of sensitivity, uncertainty and resolution for realising future quantum and nanoscale temperature standards. In the frame of this project, the Micro and Nanotechnology Institute of the Spanish National Research Council (INM-CSIC) and Centro Español de Metrologia (CEM) are involved in the design, fabrication and characterization of micro-scale thermometers based in photonic and optomechanical devices. The main requirement for reaching the high sensitivity needed for high accuracy temperature measurements is to obtain high quality factors. For photonic thermometers, a high optical quality factor is required (Qo> 105). But our design aims to be used in the future as a quantum optomechanical resonator. In this case the requirements are: high optical quality factor and high mechanical quality factor in order to obtain a high optomechanical coupling (a high f-Q product f.Q> 1012 Hz) for quantum sensitivity. With this goal, we are exploring the use of diamond-based micro and nanophotonic optomechanical resonators. Different designs will be presented and compared to same devices using traditional materials like Si and SiO2.

2.65 (BSCC) A non-equilibrium system as a demon

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Maxwell demons are creatures that are imagined to be able to reduce the entropy of a system without performing any work on it. Conventionally, such a Maxwell demon's intricate action consists in measuring individual particles and subsequently performing feedback. Here we show that much simpler setups can still act as demons: we demonstrate that it is sufficient to exploit a nonequilibrium distribution to seemingly break the second law of thermodynamics. We propose both an electronic and an optical implementation of this phenomenon, realizable with current technology.
This phenomena enables the spatial separation of the place were work is done, and the place where entropy (heat) is produced. Hence we speculate that it may have uses in heat management in nanoelectronics. Could one having a current flow in one place, and the associated Joule heating occur in another place?

2.66 (Sensing) Energetics in quantum-dot-based single-electron devices

Clemens Winkelmann [1]

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We experimentally study the effect of electron interactions and quantum correlations on the thermal conductance and thermopower of single quantum dot devices. We indeed observe a striking violation of the Wiedemann-Franz law in single-electron transistors. We further study the experimental signatures of spin-1/2 Kondo correlations on the Seebeck coefficient, which we find to be in good agreement with NRG calculations. Eventually, we demonstrate how a quantum dot junction can be used as a heat valve.

2.67 (Communication) Terrestrial free space daylight QKD at 100MHz

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Increasing the capability and capacity of classical computers, and emerging of quantum computers, the conventional encryption methods for transmitting data are proven not to be sufficiently secure. Quantum mechanics has also provided the mean to perform unconditionally secure method of encrypting data, one-time pad, through quantum key distribution (QKD) protocols. QKD in fiber, as the channel to transmit quanta of light, is already performed in relatively long distances. However, free-space QKD with laser source of 1550nm wavelength not only gives us the advantages of overcoming natural obstacles and more importantly, benefiting from the many commercially available optical instruments in telecommunication wavelength, but also is a step forward toward satellite QKD, which in comparison with fiber based QKD, suffers dramatically less from losses and is considered the only practical way to perform inter/continental QKD.

We have established and developed a free space optical channel to be used in QKD systems. Variation of the angle of arrival, beam wandering, scintillation and beam spreading are effects caused by turbulence air. By implementing a fast steering mirror (FSM), we overcome part of the errors introduced by the atmosphere, namely change in the angle of arrival along with correcting the beam wandering error and then characterize the channel. For the quantum source, we have used a 100 MHz, 1550nm wavelength laser with almost 300ps pulse width. Laser coupling to fiber is done and the total loss observed is 20db. This work shows the feasibility of a ground-satellite optical channel for use in high-speed QKD systems.

2.68 (Communication) Continuous-variable source-device-independent quantum key distribution against general attacks

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The continuous-variable quantum key distribution with entanglement in the middle, a semi-device-independent protocol, places the source in the untrusted third party between Alice and Bob, and thus has the advantage of high levels of security with the purpose of eliminating the assumptions about the source device. However, previous works considered the collective-attack analysis, which inevitably assumes that the states of the source has an identical and independently distributed (i.i.d) structure, and limits the application of the protocol. To solve this problem, we modify the original protocol by exploiting an energy test to monitor the potential high energy attacks an adversary may use. Our analysis removes the assumptions of the light source and the modified protocol can therefore be called source-device-independent protocol. Moreover, we analyze the security of the continuous-variable source-device-independent quantum key distribution protocol with a homodyne-homodyne structure against general coherent attacks by adapting a state-independent entropic uncertainty relation. The simulation results indicate that, in the universal composable security framework, the protocol can still achieve high key rates against coherent attacks under the condition of achievable block lengths.

2.69 (BSCC) Optimal probabilistic storage and retrieval of unitary channels

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The question of a quantum memory storage of quantum dynamics is addressed. In particular, we design an optimal protocol for N→1 probabilistic storage-and-retrieval of unitary channels on d-dimensional quantum systems. If we may access the unknown unitary gate only N-times, the optimal success probability of perfect retrieval of its single use is N/(N–1+d2). The derived size of the memory system exponentially improves the known upper bound on the size of the program register needed for probabilistic programmable quantum processors. Our results are closely related to probabilistic perfect alignment of reference frames and probabilistic port-based teleportation. Based on arXiv:1809.04552.

2.70 (BSCC) Nonlinear Quantum Optics in Nanophotonic Waveguides

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We develop a systematic method for deriving a quantum optical multi-mode Hamiltonian for the interaction of photons and phonons in nanophotonic dielectric materials by applying perturbation theory to the electromagnetic Hamiltonian [1]. The Hamiltonian covers radiation pressure and electrostrictive interactions on equal footing. As a paradigmatic example, we apply our method to a cylindrical nanoscale waveguide, and derive a Hamiltonian description of Brillouin quantum optomechanics. We show analytically that in nanoscale waveguides radiation pressure dominates over electrostriction, in agreement with recent experiments [2,3]. We explore the possibility of achieving a significant nonlinear phase shift among photons propagating in nanoscale waveguides exploiting interactions among photons that are mediated by vibrational modes and induced through Stimulated Brillouin Scattering (SBS) [4]. We introduce a configuration that allows slowing down the photons by several orders of magnitude via SBS involving sound waves and two pump fields. We extract the conditions for maintaining vanishing amplitude gain or loss for slowly propagating photons while keeping the influence of thermal phonons to the minimum. The nonlinear phase among two counter-propagating photons can be used to realize a deterministic phase gate. Such photon-phonon interactions are exploited in order to generate a coherent mix of photons and phonons with manifest quantum phenomena [5].

H. Zoubi, K. Hammerer, Phys. Rev. A 94, 053827 (2016).
[2] R. Van Laer, et al., Nature Phot. 9, 199 (2015).
[3] E. K. Kittlaus, et al., Nature Phot. 10, 463 (2016).
[4] H. Zoubi, K. Hammerer, Phys. Rev. Lett. 119, 123602 (2017).
[5] H. Zoubi, J. Opt. 20, 095001 (2018).

2.71 (BSCC) An individual Cr atom in a quantum dot: a spin qubit for hybrid spin mechanical systems

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Controlling single spins in semiconductors is attracting for the potential of such ultimate spin based memories in the field of emerging quantum technologies. It was shown that the spin of individual magnetic ion in a quantum dot (QD) can be probed optically. Chromium (Cr) is of particular interest: Cr is incorporated in II-VI compounds as a Cr2+ ion carrying an electronic spin S=2 with an orbital momentum L=2. The orbital momentum provides a large sensitivity of the spin to local strain making Cr2+ a promising spin *qubit* for the realization of hybrid spin-mechanical systems.
The optical probing and some optical control of the spin of a Cr atom incorporated in a CdTe/ZnTe QD were recently reported [1,2,3]. We first demonstrate here that the spin of a Cr atom can be prepared by resonant optical pumping and we show that hole-Cr flip-flops dominate the exciton-Cr spin dynamics. This spin flip mechanism appears directly in the distribution of the photoluminescence (PL) intensity under resonant excitation. A model confirms that hole-Cr flip-flops in the ns range are induced by the interplay of the hole-Cr exchange interaction and the coupling to the strain field of acoustic phonons.

In addition to the dynamics induced by carrier-Cr coupling, we demonstrate with a spatially resolved two-wavelength pump-probe experiment that a Cr spin significantly interacts with non-equilibrium acoustic phonons generated during the optical excitation inside or near the QD.

We also demonstrate that, under a resonant single mode laser field, the energy of any spin state of an individual Cr atom can be independently tuned by using the optical Stark effect.

This ensemble of optical techniques will be used for a precision sensing of externally applied strain on a Cr spin inserted in a nano-mechanical system. We will present the development of nano-mechanical system based on surface acoustic waves (SAW) and show how SAW could be used for an efficient coherent mechanical driving of a Cr spin.
[1] A. Lafuente-Sampietro, H. Utsumi, H. Boukari, S. Kuroda, L. Besombes, Phys. Rev. B 95, 035303 (2017)
[2] A. Lafuente-Sampietro, H. Utsumi, M. Sunaga, K. Makita, H. Boukari, S. Kuroda, L. Besombes, Phys. Rev. B 97, 155301 (2018)
[3] L. Besombes, H. Boukari, V. Tiwari, A. Lafuente-Sampietro, M. Sunaga, K. Makita, S. Kuroda,Phys. Rev. B 99, 035309 (2019)

2.72 (Communication) Quantum Polarization

Ashutosh Goswami [1], Fréderic Dupuis [2], Mehdi Mhalla [3], Valentin Savin [4]

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[3] CNRS UGA Grenoble – France
[4] CEA Grenoble – France

Classical Polar codes introduced by E. Arikan, are capacity achieving codes with efficient encoding and decoding algorithms for any binary-input symmetric discrete memoryless channels. Channel polarization occurs when a particular channel combining and splitting construction is recursively applied to synthesize a set of so-called virtual channels from several independent instances of a given communication channel. The synthesized channels show a polarization effect, in the sense that they tend to become either good (noiseless) or useless (completely noisy). Polar codes have already been generalized to the quantum case by Renes, Dupuis and Renner, by using classical polarization in both X or Z bases. Here, we propose a different quantum generalization of polar codes using a random Clifford as channel combining operation, where the good channels are good as a quantum channel, and not merely good in one basis. We give the decoding algorithm for Pauli channels by showing the equivalence between quantum polar code for Pauli channel and a classical polar code for symmetric, discrete, memoryless channel over four symbols input set. We also give a different proof of polarization for Pauli channels by showing the polarization for the equivalent classical channel.

2.73 (BSCC) Energy cost of entanglement extraction from Gaussian ground states

Robert Jonsson [1]

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In the ground state of many complex quantum systems there is entanglement present between spatially separate subregions of the system. This makes such systems interesting as a source of entanglement for the use in quantum information processing tasks. However, a question, only highlighted recently, is what the energetic cost of extracting entanglement from such quantum systems is.

We here calculate the energy cost of entanglement extraction from local modes of a scalar quantum field, finding scaling relations and optimalisation results. Generalizing our results to Gaussian systems we derive the minimum energy cost of entanglement extraction from the ground state of a quadratic Hamiltonian. Joint work with Terry Farrelly, Dmytro Bondarenko and Lucas Hackl.

Chapter 3

Session Education Workshop: Tuesday and Wednesday

3.1 Molecular matter-wave interference - a hands-on approach for teaching quantum mechanics

Christian Brand [1], Christiane-Maria Losert-Valiente Kroon [1], Markus Arndt [1]

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The ever-increasing impact of quantum technologies on our daily life stresses the high need to inform the general public and train users at all levels effectively in this area of research. We aim to address this challenge by pioneering new hands-on training devices for quantum technologies. Getting literally in touch with the often counter-intuitive aspects of quantum mechanics has strong advantages in deepening the learning effect, leading to citizens better prepared for future challenges. Based on our unique expertise in molecular matter-wave interference and molecular quantum metrology, we aim to realize this in several ways. On the one hand, we will build a mobile, affordable, and easy-to-use matter-wave demonstrator for education. On the other hand, we will establish an interactive app based on augmented reality to allow detailed insight into matter-wave interference and its foundation. Within a larger consortium, we propose to realize the "Virtual House of Quantum Mechanics", offering detailed and curated information on quantum technologies on all levels from basic introduction to specialized lectures on state-of-the-art research.

3.2 ESONN, European School On Nanoscience and Nanotechnology

Herve Courtois [1], Mairbek Chshiev [2], Liliana Prejbeanu [3]

[1] Université Grenoble Alpes – Université Grenoble Alpes, Université Grenoble Alpes – France
[2] Université Grenoble Alpes – Université Grenoble Alpes – France
[3] Institut polytechnique de Grenoble - Grenoble Institute of Technology – Institut Polytechnique de Grenoble - Grenoble Institute of Technology – France

From 2004, ESONN is a Grenoble-based three-week course aimed at providing training for graduate students, postdoctoral and junior scientists from universities and laboratories, all around the world, in the field of Nanosciences and Nanotechnologies. Courses cover the fundamentals of selected fields that were chosen as being important aspects of Nanosciences and Nanotechnologies, including quantum technologies. Half of the formation is devoted to practicals, which are held in Grenoble clean room facilities at the Inter-university Centre for MicroElectronics (CIME) and in research laboratories. ESONN students can choose their own practicals program from a liste of over 50 different practicals.

3.3 Multidiciplinary learning platforms on quantum engineering

David Ferrand [1]

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During the last few years, the academic researches on quantum engineering developed in Grenoble tend to become more and more integrated with the emergence of federative projects aiming to the development of the first Qbit devices. This evolution is also supported by University Grenoble Alpes through a cross disciplinary project on quantum engineering (physics, computer science, humanities) and doctoral programs [1].
Grenoble Universities and Engineer Schools are also strongly involved through a large offer of disciplinary courses spread in different Master and doctoral programs. In order to reinforce and better structure the teaching offer at the Master level, a new training program in quantum engineering will open in September 2019 (funding from the Idex program of the Comue Université Grenoble-Alpes [2]). The aim of this program is to set-up two innovative and multi-disciplinary learning platforms. The first platform will be dedicated to quantum computing. It will be based on the implementation of elementary quantum algorithms on quantum computers and simulators (IBM-Q platform) and on their analyses under the supervision of physicists and computer scientists. The second platform will be dedicated to the basis of quantum communication protocols. The students will work on a quantum optics experimental set-up and develop experiments based on the generation and manipulation of single photons and entangled photon pairs. These platforms will be open in different Grenoble Master Programs (see [3]): Master 2 Nanophysics (UFR phitem-UGA), EMNano+ Erasmus-mundus Master, Master of Science in Industrial and Applied Mathematics (UFR IM2AG-UGA), 2nd year students of the engineer school ENSIMAG-Grenoble-INP. It will bring together students from different backgrounds in the same course, with the aim of becoming the future key players in the field.

Quantum Engineering Cross Disciplinary Program, https://quantum.univ-grenoble-alpes.fr/quantum-engineering-708453.htm?RH=15058122

https://www.communaute-univ-grenoble-alpes.fr/en

https://master-nanosciences.univ-grenoble-alpes.fr/, http://www.emm-nano.org/ , http://msiam.imag.fr, http://ensimag.grenoble-inp.fr/en

3.4 Quantum games and simulations for research, education and outreach

Jacob Sherson [1], Shaeema Zaman Ahmed

[1] ScienceAtHome, Center for Hybrid Intelligence, Department of Physics and Astronomy, Aarhus University – Denmark

In the www.scienceathome.org project, we have developed gamified interfaces allowing so far 300,000 players to contribute to research by providing insightful seeds for quantum optimization algorithms (Quantum Moves, Nature) and remote access to our ultra-cold atoms experiment for amateur scientists, students, and researchers (The Alice Challenge, PNAS).
Also, within the www.quatomic.org project, we have creates the visual programming tool, Quantum Composer, to enable intuition-based theoretical quantum research as well as a non-formalistic and powerful introduction to university level quantum education.
Over the past couple of years we have incorporated both Quantum Moves and Quantun Composer into high school and introductory and advanced quantum mechanics university teaching. Most recently, in December 2018 we held a national research competition, ReGAME Cup, in which 2500 high school students competed in generating novel science and going through associated learning trajectories. In the coming couple of years we will be conducting a large scale Randomized Control Trial on 150 Danish schools to test whether this form of research-creating game-based education can enhance student motivation and learning.

3.5 Teaching Quantum Physics - Some experiences at University of Bologna

Elisa Ercolessi [1], Olivia Levrini , Ravaioli Giovanni

[1] Dept. Physics and Astronomy - University of Bologna – Italy

I will present the collaboration between the group of History and Didactics in Physics and some members of the Theoretical Physics group of the University of Bologna to develop several programs that have been led in recent years for teaching Quantum Physics at the level of high-school, with both students and teachers.
The projects aim at giving a rigorous introduction to disciplinary topics, focusing on the conceptual aspects of quantum mechanics and with emphasis on the most recent developments and applications. We favor a multidisciplinary approach, with also the goal to promote STEM disciplines and enhance students' ability to imagine the future.
(Remark: the poster will be submitted by Giovanni Ravaioli)

3.6 ISEE ERASMUS+ project and Quantum Computing: a STEM approach to engage with the logic and the social impact of Quantum Physics

Giovanni Ravaioli [1], Elisa Ercolessi [1], Paola Fantini [2], Antti Laherto [3], Elina Plamgren [3], Sara Satanassi [1], Olivia Levrini [1]

[1] University of Bologna – Italy
[2] Liceo A. Einstein, Rimini – Italy
[3] University of Helsinki – Finland

The EU ERASMUS+ project I SEE (Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers) bets on STEM education as a breeding ground for preparing young people for uncertainty and making them developing future scaffolding skills, i.e. skills that enhance their capacity to aspire, envisage themselves as agents of change, and push their imagination towards future careers in STEM. One of the goals of the project is to design teaching/learning modules for high schools; the addressed issues are very different (e.g. climate change, artificial intelligence, quantum computing), but all the modules share a common structure in which the students are encouraged to: i. encounter the focal issue from a cultural and social perspective; ii. engage with the core scientific ideas of the topic; iii. project themselves into possible, plausible and probable futures, and identify a desirable one to reach with actions in the present. The teaching module on quantum computing, designed within a collaboration between the University of Bologna and the University of Helsinki, is built upon the analogy between the evolution of classical computers/algorithms and the present ongoing research on quantum computing, using the lens of the abstraction passage from a physical (mechanical, electrical, or 'quantum') signal to a logical information. The new logic of qubits and entanglement is introduced with a spin-first approach, using Stern-Gerlach experiments; in order to engage with the future(s), the students are guided through the 'Quantum Manifesto' and to the exploration of the quantum computing applications. In this perspective, the logic of quantum cryptography and teleportation experiments are presented, making use of didactical simulations. Finally, the students are guided in future-oriented activities, to let them individuate their desirable future and plan actions to make them possible. We believe that the integration of the S-T-E-M disciplines, together with the future-oriented activities, can allow science to re-assume its orienting role in understanding the complexity of our society.

3.7 Introductory quantum physics through Feynman's sum over paths approach

Massimiliano Malgieri [1], Pasquale Onorato [2], Anna De Ambrosis [1]

[1] University of Pavia – Italy
[2] University of Trento [Trento] – Italy

The Physics Education group at the University of Pavia is working since 2013 on a proposal for the teaching of quantum physics introductory level using Feynman's sum over paths approach. Sum over paths is an educational reconstruction of quantum physics based both on Feynman's path integral formulation, and the divulgative version Feynman himself used in the book *QED: the strange theory of light and matter*. Feynman's approach offers several educational advantages: 1) it allows to clearly identify the conceptual core of quantum physics as the way to compute probabilities for events which can happen in several alternative, indistinguishable ways; 2) it offers to students the possibility to handle a working model of quantum theory, allowing to solve many different problems (belonging to certain classes) rather than having separate formulas valid only for an individual problem or phenomenon; 3) thanks to the strategy of representing complex amplitudes as phasors or "little arrows", it uses very little advanced mathematics; and 4) it offers to teachers the possibility of discussing relatively recent experimental evidence, especially from the field of quantum optics, such as the Zhou-Wang-Mandel or Hong-Ou-Mandel experiments, which are most naturally described in terms of Feynman paths. Over the years we have developed the educational reconstruction of quantum physics based on Feynman's formulation to become a very flexible instrument in the hands of instructors and researchers for building teaching-learning sequences with different breadth and flavour. For example, we have tested a "minimal" version, in which the photon model is introduced in parallel with the wave theory of light, in the fourth year of Italian "Liceo Scientifico" (17-18 year old students) ; a version for the fifth year of Liceo (18-19 year old students), covering all the suggested material in the Italian curiculum, and extending it in the direction of discussing modern experiments in quantum optics; and a version we use for teacher education, with a broader scope, covering in more detail bound quantum systems, the tunnel effect, processes in which more than one quantum object is involved.

Malgieri, M., Onorato, P., De Ambrosis, A. (2017) Phys. Rev. Phys. Ed. Res. 13(1).
Malgieri, M., Onorato, P., De Ambrosis, A. (2014) Eur. J. Phys. 35(5).

3.8 Quantum education – the milq approach

Rainer Mueller [1], Oxana Mishina [1]

[1] TU Braunschweig – Germany

In Germany, quantum physics has been an established part of the schools physics curriculum for several decades. There is a considerable amount of experience and research on teaching and learning of quantum physics in secondary school. We present the central ideas of our online-based course **milq.** The milq course focuses on conceptual questions with a minimum of formulas. It is based on a modern, pragmatic interpretation of quantum mechanics which has emerged since the 1990s together with the experimental possibility to actually perform experiments with single quantum objects. The aim is a conceptually clear formulation of quantum physics. In order to provide students with verbal tools they can use in discussions and argumentations we formulated four "Reasoning tools" of quantum physics. They help to enable qualitative discussions of quantum physics, allow students to predict quantum mechanical effects qualitatively and help to avoid learning difficulties. They form a "beginners' axiomatic system" for quantum mechanics. We will also sketch our ideas for the future of quantum education within the framework of the Flagship.

3.9 A combination of the two-states and matter-wave approaches to teach concepts of quantum mechanics

Sergej Faletic [1], Tomaz Kranjc [2]

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[2] University of Ljubljana, Faculty of Education – Slovenia

At the University of Ljubljana, a sequence for teaching QM in high schools was developed using a two-state system combined with a matter-wave approach. It is the second iteration of a design-based research. The first iteration did not use the two-state system and was heavily dominated by a matter-wave approach, using carefully developed classical-wave analogies to build a wave-intuition in students, complementing it later with specific quantum phenomena. In the second iteration, the two-state part was introduced to familiarize the students with the concept of state and measurement. A simulation of measurements in a double well environment is used, with a left and right position states as a basis. Exploring the simulation, students learn the indeterminism of individual results, the determinism of probability, the concept of state and superposition, and the role of measurement and collapse. Next, they explore the time evolution and the stationary and non-stationary states. A simulation of a double slit experiment is used to introduce the necessity of a wave-like description of the probability distribution, and discuss the "which way" problem. The wave-like description is then used to explore stationary states in an atom, modelled as a single infinite well, and relate the findings to the shapes of the orbitals, a topic already covered in chemistry. The wave-like description is also related back to the probability distribution in the double well, explored before. The lowest two energy eigenstates are introduced as a second basis for the double well. Results of subsequent measurements of position and energy in the double well are used to discuss the difference between a superposition and a statistical mixture of states. The sequence has been used in a class of 20 students aged 17-18. Analysis of pre-tests, post-tests, exams, formative assessment and questionnaires were combined to arrive at conclusions about what are the most important concepts for the students, what have they learned, and what kind of reasoning they developed regarding the selected topics. Collapse emerged as a foothold idea for the students, so it will be given special attention in future iterations.

3.10 European Patent Office

Nigel Clarke [1], Maria Oliete Ballester [1], Julia Diana Moreira Dias [1]

[1] European Patent Office – Germany

The European Patent Office is the patent office for Europe. We are not an EU institution but we are an intergovernmental organisation in Europe. We have 38 full member states. We take patent applications from all around the world and grant them to take effect in any or all of our European member states.
All patent offices around the world are obliged to publish the patent applications they receive. Patent applications contain detailed and unique technical and scientific information about the inventions in those applications.

The EPO collects all of those technical patent publications from around the world and makes them freely available to anyone who can use them: researchers, academics, entrepreneurs and those in leading edge physics-based enterprises.

The EPO also provides training in how to retrieve and apply the information in patents for R&D, and business development.

We also provide training in other activities involving Intellectual Property (IP) such as IP protection, IP management and IP enforcement.

In parallel with the EU Quantum Technology (QT) Flagship launch, we published a patent landscape study which tracks the evolution from quantum science research results in the lab to quantum technology products in the market.
We are developing tailored training modules, materials, and case studies for QT researchers and entrepreneurs and we have further QT patent landscape studies lined up for the future.

3.11 Quantum Rules! A high school visitors lab

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The Depts. of Physics and Astronomy at Leiden University maintain an intensive relation between physics teachers and their students of regional high schools. The core of the **teachers' network** (600 subscriptions) are three annual teachers meetings (200 visitors/yr), in which we inform our network on developments in science and didactics. The teachers are our guests, we welcome them with a good meal and the meetings are free of charge. We employ various activities, of which some are related to quantum. We support the quantum in the physics curriculum with biannual teachers' courses on quantum (30 participants/2yr). We also use the network to recruit authors and testers for a science module on quantum computing, to be developed in the coming years. Through the teachers network we also can reach exam-grade students. We help individual students with their final assignments (40 students/yr). We run a **high-school lab** (800 visitor/yr) under the name Quantum Rules! (www.quantumrules.nl)'. This lab houses about twenty experiments that cover the quantum aspects of the physics curriculum (pre-university level). Classes of up to up to 30 students come in daily visits. In the morning they perform quantum-related experiments. During lunch they attend a lunch-lecture, and students present their results in the afternoon. As a constraint for the presentations we require them to present all their results condensed in four presentations. Thus, we teach them to make connections between the rules of quantum. Currently we are implementing a new element to this lab. In a web-based, escape room-like **game** we help students discover how quantum rules our daily lives (e.g. in sustainability, medical and communications technology). Thus, we aim to raise the **quantum awareness** of high-school students at a point in their lives that is pivotal for their career choice.

3.12 Educational path proposals on modern physics and in particular quantum mechanics by means of two-states system

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At the University of Udine, a series of educational proposal for modern physics in secondary school and in the first two years of university are developed. Educational paths are relative to Diffraction, Optical Spectroscopy, Rutherford Backscattering Spectroscopy, Cross Section, Electrical Transport Properties of matter, Superconductivity, Mass-Energy, Quantum Mechanics (QM).
The rationale of the course in QM focuses on the concept of state and the superposition principle. The linear polarization was chosen as a quantum dynamical property of photons. It is explored in the lab by means of simple hands-on experiments and of quantitative measurement with on-line sensors. Starting from the experimental Malus law, students learn how to prepare and detect polarized light. The polarization as a property of a single photon is confirmed by the validity of Malus law at very low light intensity and suggests to interpret it as the probability of photon transmission. An open environment simulation system (JQM) offers the opportunity to explore ideal experiments and to develop interpretative ideas. An iconographic representation is used to help students distinguish between the property (eigenvalue) and the state (eigenvector). A sequence of situations with interactions between photons and polaroids is used to identifymutually exclusive and incompatible properties, and build the quantum description of phenomena by means of vectors and projectors in two dimensional space. The uncertainty principle, the quantum indeterminism, the identity of quantum systems are basic concepts discussed. The interaction of photons with birefringent crystals explores the impossibility of attributing a trajectory to a single photon (a quantum system). The problem of quantum theory of measurement, of describing macro-objects and non-locality are treated in the same context, with examples in the phenomenology of particle diffraction and analogies in the macroscopic world.
Research experimentation was performed with 694 students aged 17-19 and 100 university students of math degree. Qualitative analysis of tutorials and tests was performed. Profiles distinguishing between the classical and quantum points of view, and also individuating ides coherent with a hidden variable approach, emerged in the analysis of students' reasoning.

3.13 Quantum technologies meet Condensed Matter @ Sorbonne Université

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Materials properties at the nanoscale can be radically changed by means of size, crystal structure or surface states. With modern technologies it is now possible to access and observe the quantum aspects of materials at a deeper level and discover novel properties and states of the matter, as for example, topological states. Defects in solids are not more undesirable but they become very good condensed matter qubits as the nitrogen-vacancy in diamond. Very important progress has also been done recently in the domain of the material synthesis leading to realization of complex structures or networks of artificial atoms for quantum communication and cryptography. In last years, new materials as the graphene has been discovered. Each breakthrough in material sciences is at the heart of quantum technologies. The master degree in "Material and Nano-objects Sciences" at Sorbonne Université, in Paris France, aims to give to master students basic knowledge necessary for the development of the field of quantum technologies based on materials and offers comprehensive high-level theoretical and experimental training on the structural and electronic properties of condensed matter and nanostructures. It is associated to laboratories of Sorbonne Université working in high-quality fundamental research on condensed matter using advanced experimental and theoretical methods.

3.14 Quantum SpinOff - The physics of the very small with great applications

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The Quantum Spinoff project brings science teachers and their pupils in direct contact with research and entrepreneurship in the high-tech nano sector, with the goal of educating a new generation of scientifically literate European citizens and inspiring young people to choose for science and technology careers. Teams of pupils, guided by their science teachers create a responsible and socially relevant valorization of a scientific paper in collaboration with actual researchers and entrepreneurs. They first study quantum physics in school through the Quantum SpinOff learning stations: they follow a conceptual approach and use for instance the analogy between musical standing waves and quantization of electron waves in the atom. The learning path is also supported by hands-on experiments like the measurement of Planck's constant with LEDs, the measurement of the emission lines of hydrogen, etc. After this conceptual introduction, the pupils come in contact with the real world of quantum technology: they visit high-tech research labs and compete for the European Quantum Spin-Off Prize. Scientific and technological insights, creativity and responsible entrepreneurship are all taken into account by a jury of experts. Science teachers are trained in international and national workshops to support the inquiry learning process of their pupils. The project won the Scientix Resources Award in the Category: STEM-learning materials for students. It received a final score of 80% by the European Commission and it was mentioned in a list of interesting practices as an annex to the report "Science education for responsible citizenship", prepared by a Science Education Expert Group (SEEG) nominated by the Commission. The aim of this report was to support the preparation of the new Science Education policy initiatives and policy options and to develop specific actions to be included in the Science with and for Society (SwafS) work programs. You can find the Quantum Spinoff project also in the Scientix portal.

3.15 Visualizations and Augmented Reality for Physics Education of Quantum Technology topics

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WARNING: our group will not be able to be present at the conference: we still decided to submit the abstract because we are really interested in being part of the Education Research community connected to the QT flagship and we hope to reach some of the participants through it.

Many authors outlined the students' difficulties in the conceptual understanding of quantum physics. A lot of research has been done using computer visualizations of quantum mechanical (QM) topics and it proved to be a powerful and flexible tool both for research and for physics education.

In the last years, our group worked on the design, development and testing of visualizations and hardware/software setups for physics education.

As an example, we released an iOS app named "Hydrogen!" for the discussion of several topics of QM using the hydrogen bound states [1]. For example, these visualizations allow students to interactively create any superposition of bound states and to see how they interfere with each other. The time evolution of such superpositions (and their moduli) may also be visualized, allowing to understand the meaning of a stationary or a non-stationary state.

As a second example, we developed an augmented reality setup based on a 3D camera and a projector to discuss many topics ranging from motion to wave propagation, *augmenting* real experiments and also mixing them with simulations [2][3]. It is based on the capability of obtaining 3D reconstructions of the physical world which can be visualized both live as the data is acquired and later on as interactive playbacks. The setup allows to obtain 3D tracking of multiple objects [1], to project data of interest directly on the objects used in a real experiment, and to introduce the new concept of "augmented experiments". The setup was tested with a group of university students and as a scientific exhibit for hands-on activities.

Our goal within the QT flagship would be to work on the use of visualizations and virtual and augmented reality for physics education of QT topics.

[1] *"A bit of quantum mechanics"*, S. Oss, T. Rosi, Phys. Teach. 53, 230, 2015
[2] *"Multiple object, three-dimensional motion tracking using the Xbox Kinect sensor"*, T. Rosi, P. Onorato and S. Oss, European Journal of Physics, 38, 6, 2017
[3] *The Augmented Laboratory* website, https://augmentedlaboratory.wordpress.com/

3.16 Smart tools for hands-on quantum physics education

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One of the most effective ways of learning and understanding phenomena or concepts of nature is to get hands-on experience. Unfortunately, quantum physics experiments require a lot of preparation time and are oftentimes sensitive to external influences. Therefore, quite often many effects are only taught theoretically.
Our vision is that quantum physics shall be delivered also in an experimental, phenomenological way. Not only live demonstrations of quantum optics experiments, but also the chance for everyone to set up their own experiments and to record and evaluate their own results. In that sense we believe that fascination is the main key to win over people for the Second Quantum Revolution.

Yet this process has to start earlier and broader than the recent approaches. The understanding and the possibility to get access to the world of quantum physics at the moment is constraint to a rather small group of physicists and (physics) students. The vast majority of European citizens, or generally laymen, do not have a real chance to get even a real glimpse on the ongoing research, the status quo, the progress or even the need for putting efforts into this field.

We want to apply a fundamental change to the general attitude towards quantum physics and the methods for teaching. In order to convey the importance of quantum physics to the current and future generations, it is necessary to make its basic principles accessible to the society as a whole.
One of our approaches was and is the so-called Quantenkoffer. The Quantenkoffer enables a practical revision of the basic principles of quantum physics and ensures that this knowledge reaches the people – in schools, universities, but also into public space. It is important to include all parts of society, such that the opportunities come across. There should be no forbidden questions and an open discussion is one of the many mandatory foundations for physics in general, but also for a peaceful future in an open-minded, pluralistic and globalized world.

*Speaker

3.17 GIREP vzw, the International Research Group on Physics Education.

Wim Peeters * [1]

[1] GIREP vzw – Belgium

GIREP is a legal entity, a service organisation for the worldwide physics education research community. GIREP focuses on bringing researchers and other stakeholders together to enhance physics education. GIREP uses several ways of doing this:
- Via 8 (in the near future 9) GIREP Thematic Groups (GTG's) that have specific focuses in the field of physics teaching and learning

- By organising yearly conferences and seminars with partner organisations, and 4- yearly World Conferences of Physics Education

- Via publications (on line and hard copy) of proceedings and selected papers, as well as thematic books in this field

- By elaborating cooperation in written agreements with organisations from all over the world
In a close collaboration we can offer the Quantum Technologies Project- Education section many opportunities in the field of education.

*Speaker

3.18 Project ReleQuant: a research-based learning resource in modern physics for upper secondary school

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The Norwegian project ReleQuant develops digital, research-based learning resources in quantum physics and general relativity for upper secondary school. It is a design-based research project with the dual aim of offering validated learning resources for use in schools, and performing research on student understanding and learning within modern physics. Practicing physics teachers and physics teacher students are included in the work.
Web-based learning resources have been developed based on previous research on learning challenges and on results from several rounds of classroom trials. Students' written and oral responses to problems and assignments have been collected and analysed along with sound recordings of student small-group discussions. Also, focus group data have been collected to capture students' own account of their motivation, learning and challenges when working with the ReleQuant material. The learning resources are found at www.viten.no/eng/.

The ReleQuant group has published research on topics such as students' understanding of wave-particle duality and of the Schrödinger's cat thought experiment; on student learning through small-group discussions of quantum physics; on the role of the rubber sheet analogy in students' learning of general relativity, and more (www.mn.uio.no/fysikk/english/research/projects/relequant/).

Results from ReleQuant may be of relevance for education and training in quantum technologies in several ways: 1) through improving teaching and learning quantum physics in schools; 2) through extending our research and development into physics higher education contexts; and 3) through providing a background for developing communication efforts about quantum technology aimed at the general public.

*Speaker

3.19 Quantum Physics Education R&D @ Twente and Utrecht

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Quantum experiments for wave-particle duality and tunneling have been designed with concept tests that help measure learning effects. Bouncing droplets were explored to see if they could give some macro analogy for quantum behaviour (Sleutel et al, 2017). Further work on quantum simulations is in progress (Vilarta Rodriguez, 2018). This relates both to simulations but also to online tools that can help compose online lesson scenarios wrapping all sorts of resources such as instructions, videoclips, simulations (GoLab, 2019). Lesson scenarios can be shared and edited by each teacher. Apart from a series of master theses, two PhD theses are underway with regard to student understanding of quantum concepts (Krijtenburg-Lewerissa et al, 2017). In our projects we combine quantum physics, educational science and field expertise from physics teachers that co-create and test new designs. Apart from classical methods such as reviews and Delphi studies we also apply learning analytics and lesson study methods that give a closer look on how learning activities are working out in practice. Finally in the production of educational video's we are working on innovative technologies such as the lightboard (see https://www.youtube.com/watch?v=eY1gDgH7Zxc) and means to make studying these videos more interactive.

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*Speaker

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