Book of abstracts

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Chapter 1

Tuesday - 14:00-15:45 : BSCC - 1 (Platine)

Routing thermal noise through quantum networks

Shabir Barzanjeh [1], Matteo Aquilina [2], André Xuereb * [3]

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There has been significant interest recently in using complex quantum systems to create effective non-reciprocal dynamics. Proposals have been put forward for the realisation of artificial magnetic fields for photons and phonons; experimental progress is fast making these proposals a reality. Much work has concentrated on the use of such systems for controlling the flow of signals, e.g., to create isolators or directional amplifiers for optical signals. In this talk, we build on this work but move in a different direction. We develop the theory [1,2]of and discuss a potential realization for the controllable flow of thermal noise in quantum systems. We demonstrate theoretically that the unidirectional flow of thermal noise is possible within quantum cascaded systems. Viewing an optomechanical platform as a cascaded system we show here that one can ultimately control the direction of the flow of thermal noise. By appropriately engineering the mechanical resonator, which acts as an artificial reservoir, the flow of thermal noise can be constrained to a desired direction, yielding a thermal rectifier. The proposed quantum thermal noise rectifier could potentially be used to develop devices such as a thermal modulator, a thermal router, and a thermal amplifier for nanoelectronic devices and superconducting circuits.
References

[1]S. Barzanjeh, M. Aquilina, and A. Xuereb, Phys. Rev. Lett., **120**, 060601 (2018).
[2]A. Xuereb, M. Aquilina, and S. Barzanjeh, Proc. SPIE **10672**, 10672N (2018).

*Speaker

Optical Backaction-Evading Measurement of a Mechanical Oscillator

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Quantum mechanics imposes a limit on the precision of a continuous position measurement of a harmonic oscillator, as a result of quantum backaction arising from quantum fluctuations in the measurement field. A variety of techniques to surpass this standard quantum limit have been proposed, such as variational measurements, stroboscopic quantum non-demolition and two-tone backaction-evading (BAE) measurements. The latter proceed by monitoring only one of the two non-commuting quadratures of the motion. This technique, originally proposed in the context of gravitational wave detection, has not been implemented using optical interferometers to date. Here we demonstrate continuous two-tone backaction-evading measurement in the optical domain of a localized GHz frequency mechanical mode of a photonic crystal nanobeam cryogenically and optomechanically cooled in a 3He buffer gas cryostat close to the ground state. Employing quantum-limited optical heterodyne detection, we explicitly show the transition from conventional to backaction-evading measurement. We observe up to 0.67dB (14%) reduction of total measurement noise, thereby demonstrating the viability of BAE measurements for optical ultrasensitive measurements of motion and force in nanomechanical resonators.

*Speaker

Entanglement preserving local thermalization

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In this paper we investigate whether entanglement can survive the thermalization of subsystems. We present two equivalent formulations of this problem: 1. Can two isolated agents, accessing preshared randomness, locally thermalize arbitrary inputs while maintaining some entanglement? 2. Can thermalization with local heat baths, which may be classically correlated but do not exchange information, locally thermalize arbitrary inputs while maintaining some entanglement? We answer these questions in the positive at every nonzero temperature, and provide bounds on the preserved entanglement. We provide explicit protocols and discuss their thermodynamic interpretation; we suggest that the underlying mechanism is a speed-up of the subsystem thermalization process. We also present extensions to multipartite systems. Our findings show that entanglement can survive locally performed thermalization processes accessing only classical correlations as a resource.

*Speaker

Preparation and detection of a phonon Fock states at room temperature

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Mechanical oscillators have become essential technological building blocks, but their manipulation in the quantum regime remains very challenging. In particular, they do not generically exist in an excited Fock state. It is only by careful engineering and isolation of GHz-frequency nano-scale oscillators, and operation at milli-Kelvin temperatures, that experimenters recently achieved quantum state preparation. Here, we achieve this in ambient conditions, by using ultra-fast laser pulses and time-correlated single photon counting to create non-classical phonon states of Raman-active vibrational modes in a crystal at 40 THz [1,2].
First, we send a femtosecond laser pulse on a Raman active material, where spontaneous Stokes scattering leads to the creation of an entangled photon-phonon state (a two mode squeezed state). Performing single-photon detection (a projective measurement) on the Stokes mode permits the probabilistic preparation of the n = 1 phonon Fock state. We then send a second pulse to map the phonon quantum state onto a propagating anti-Stokes photon. By controlling the delay between the two pulses we are able to witness the decay of the vibrational Fock state over its 3.9 ps lifetime at room temperature.

By using a Hanbury-Brown and Twiss interferometer on the anti-Stokes signal we verify the sub-Poissonian statistics of the phonon mode, demonstrating the successful preparation of the n=1 Fock state, and showing that this method can also be used to produce heralded single photons.

References :
[1]Anderson, Mitchell D., Santiago Tarrago Velez, Kilian Seibold, Hugo Flayac, Vincenzo Savona, Nicolas Sangouard, and Christophe Galland. "Two-Color Pump-Probe Measurement of Photonic Quantum Correlations Mediated by a Single Phonon." Physical Review Letters 120, no. 23 (2018): 233601.
[2]Velez, Santiago Tarrago, Kilian Seibold, Nils Kipfer, Mitchell D. Anderson, and Christophe Galland. "Room-temperature heralded vibrational state exhibiting sub-Poissonian statistics." *arXiv preprint arXiv:1811.03038* (2018).

*Speaker

Electron quantum optics and quantum signal processing

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Although optical beams and classical electrical current have been used as carriers of classical information for decades, understanding precisely the quantum signals carried by quantum photonic beams and quantum electrical currents is still an open problem. In the recent years, the recent progresses of electron quantum optics, an emerging branch of electronic transport aiming at generating, manipulating and characterizing elementary excitations of the electronic fluid, similarily to what is done in photon quantum optics [E. Bocquillon *et a*l, Annalen der Physik **526**, 1 (2014)]has given up a new window on this question.

In this talk, I will lay down the basics of quantum signal processing, an enabling quantum technology that aims at enabling us to understand what are the quantum signals carried by such quantum electrical currents, how they can be processed, represented and analyzed. To illustrate these concepts, I will discuss how these quantum signals are encoded within the electronic coherences defined by analogy with the Glauber quantum optics coherences and I will show how they encode the various single and more generally many-electron wavefunctions propagating within the conductor. I will then review how electronic interferometry experiments can be interpreted in terms of quantum signal processing operations relating electronic quantum coherences to experimentally observable classical signals [B. Roussel *et al*, Physica Status Solidi **254**, 1600621 (2017)]. Finally, I will show how to extract the elementary electronic atoms of signal contained within a given quantum electrical current, thus demonstrating for the first time the extraction of individual electron and hole wave functions carried by such a quantum electrical current [see ArXiv:1710.11181].

*Speaker

Minimal Excitations in the Fractional Quantum Hall Regime

Jérôme Rech * [1], Dario Ferraro [2], Flavio Ronetti [3,4], Luca Vannucci [5], Matteo Acciai [2,6,7], Thibaut Jonckheere [8], Maura Sassetti [5,9], Thierry Martin [7]

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Single electron sources have opened up the way to the realization of electronic interferometers involving the controlled preparation, manipulation and measurement of single electron excitations in ballistic conductors, therefore emulating quantum optics experiments to the realm of mesoscopic physics.

One such source consists in applying properly quantized Lorentzian voltage pulses to the contacts of a quantum conductor, thus emitting electrons in the form of minimal excitations states, called "levitons". Their peculiar properties offer exciting new applications in quantum physics. However, the fate of such states in the presence of interactions is still an open problem.

We propose to study the minimal excitation states of fractional quantum Hall edges, extending the notion of levitons to interacting systems. Interaction and quantum fluctuations strongly affect low dimensional systems leading to dramatic effects like spin-charge separation and fractionalization. This is particularly true when the ground-state is a strongly correlated state, as are the edge channels of a fractional quantum Hall (FQH) system.

Using both perturbative and exact calculations, we show that minimal excitations arise in response to a Lorentzian potential with quantized flux. They carry an integer charge, thus involving several Laughlin quasiparticles (anyons), and leave a Poissonian signature in a Hanbury-Brown and Twiss partition noise measurement at low transparency.

They are further characterized in the time domain using Hong-Ou-Mandel interferometry, revealing some peculiar features in the case of multiply charged Levitons in the form of additional

*Speaker

side dips in the computed noise. These dips are concomitant with a regular pattern of peaks and valleys in the charge density, reminiscent of analogous self-organization recently observed for optical solitons in nonlinear environments, ultimately suggesting some kind of crystallization mechanism.

Zero-field magnetometry based on nitrogen-vacancy ensembles in diamond

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Ensembles of nitrogen-vacancy (NV) centers in diamonds are widely utilized for magnetometry, magnetic-field imaging and magnetic-resonance detection. At zero ambient field, Zeeman sublevels in the NV centers lose first-order sensitivity to magnetic fields as they are mixed due to crystal strain or electric fields. In this work, we realize a zero-field (ZF) magnetometer using polarization-selective microwave excitation in a 13C-depleted crystal sample. We employ circularly polarized microwaves to address specific transitions in the optically detected magnetic resonance and perform magnetometry with a noise floor of 250 $pT/\sqrt{Hz}$. This technique opens the door to practical applications of NV sensors for ZF magnetic sensing, such as ZF nuclear magnetic resonance, and investigation of magnetic fields in biological systems.

*Speaker

Chapter 2

Tuesday - 14:00-15:45 : Computing - 1 (Auditorium)

A linear Paul trap for catching, sympathetic cooling, identifying and shooting out ions: Applications in quantum information

Schmidt-Kaler Ferdinand * [1]

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Paul traps allow for confining a large range of atomic and molecular ions. I introduce methods for trapping and identifying sympathetically cooled ions, either in a non-destructive manner from the voids in the laser-induced calcium fluorescence pattern emitted by the crystal, and alternatively, by means of a time-of-flight signal when extracting ions from the Paul trap and steering them into an external detector [1,2]. In a first application we cool single 141Pr+ ions, and focus them into a YAG-crystal, forming nm-sized patterns of single deterministically positioned optical active centers. Such accurately positioned arrays of rare earth ions, detected by our Stuttgart collaborators(a) may further serve for a solid state quantum simulator [3]. Aiming for a spot size below 5nm we develop a new ion implanter machine, which will be instrumental for the fabrication of interacting P-qubits in Silizium [4]to be tested by our Australian collaboration(b).

(a) T. Kornherr, R. Kolesov, J. Wrachtrup, 3. Physikalisches Institut, Univ. Stuttgart,

(b) D. Jameson et. al., Univ. of Melbourne, CQC2T References:

[1]Jacob et al, Phys. Rev. Lett. 117, 043001 (2016)

[2]Grooth-B. et al, arXiv:1807.05975 (2018)

[3]J. Perczel et al,Phys. Rev. Lett. 119, 023603 (2017)

[4]Tosi et al. Nat. Com. 8, 450 (2017)

*Speaker

A Shuttling-Based Trapped Ion Quantum Processing Node

Ulrich Poschinger * [1], Janine Hilder [1], Daniel Pijn [1], Vidyut Kaushal [1], Alexander Stahl [1], Björn Lekitsch [1], Ferdinand Schmidt-Kaler [1]

[1] Universität Mainz – Germany

Reaching scalability remains the biggest challenge to overcome for realizing useful quantum computers. For trapped ion quantum computing, a possible solution is to store atomic qubits in segmented radio-frequency traps and move these within the trap array by changing the control voltages applied to the segments [1]. This circumvents the problems of storage and addressing of ions occurring for large Coulomb crystals.
In this contribution, we present the architecture of a small shuttling-based trapped ion quantum processing node, currently capable of full control over up to six qubits. We describe the key components of the system: The segmented ion trap, the fast multi-channel arbitrary waveform generator controlling the ion movement and the 40Ca+ spin qubits. We analyze the interplay of the components, address the limitations arising from these and describe required future developments.

Furthermore, we report on recent results based on our architecture: Characterization of the shuttling operations as operational building blocks [2], entanglement enhanced magnetometry [3], sequential generation of multipartite entanglement [4]and ongoing work on fault-tolerant error syndrome readout.

References:

[1]D. Kielpinsky et al., Nature **417**, 709 (2002)
[2]A. Walther et al., PRL **109**, 080501 (2012), T. Ruster et al., PRA 90, 033410 (2014), H. Kaufmann et al., PRA **95**, 052319 (2017)
[3]T. Ruster et al., PRX **7**, 031050 (2017)
[4]H. Kaufmann et al., PRL **119**, 150503 (2017)

*Speaker

Non-Abelian adiabatic geometric transformations in a cold Strontium gas

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[2] MajuLab, CNRS-UCA-SU-NUS-NTU International Joint Research Unit – Singapore
[3] Centre for Quantum Technologies, National University of Singapore – Singapore

Topology, geometry, and gauge fields play key roles in quantum physics as exemplified by fundamental phenomena such as the Aharonov-Bohm effect, the integer quantum Hall effect, the spin Hall, and topological insulators. The concept of topological protection has also become a salient ingredient in many schemes for quantum information processing and fault-tolerant quantum computation. The physical properties of such systems crucially depend on the symmetry group of the underlying holonomy. We present our work on a laser-cooled gas of strontium atoms coupled to laser fields through a 4-level resonant tripod scheme [1]. By cycling the relative phases of the tripod beams, we realize non-Abelian SU(2) geometrical transformations acting on the dark-states of the system and demonstrate their non-Abelian character. We also reveal how the gauge field imprinted on the atoms impact their internal state dynamics. It leads to a new thermometry method based on the interferometric displacement of atoms in the tripod beams.

[1]F. Leroux, K. Pandey, R. Rebhi, F. Chevy, C. Miniatura, B. Gremaud, and D. Wilkowski, *Non-Abelian and adiabatic geometric transformation in a cold atomic gas*, Nature Communications **9**, 3580 (2018).

*Speaker

Quantum Information Processing using Trapped Atomic Ions and MAGIC

Christof Wunderlich * [1], Hans J. Briegel [2], Vedran Dunjko [3], Elham Esteki [1], Nicolai Friis [4], Gouri Shankar Giri [5], Timm Florian Gloger [1], Michael Johanning [1], Delia Kaufmann [1], Peter Kaufmann [1], Alexander Kraft [1], Bogdan Okhrimenko [1], Moritz Porst [1], Theeraphot Sriarunothai [1], Sabine Wölk [1]

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[2] University of Innsbruck – Austria
[3] University of Leiden – Netherlands
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[5] University of Düsseldorf – Germany

Trapped atomic ions are a very well characterized physical system for quantum information science (QIS) and its applications. When considering the scalability of trapped ions, the use of laser light for coherent operations turns out to give rise to technological issues, and to difficulties rooted in the physics related to trapped ions. In suitably modified ion traps that allow for magnetic gradient induced coupling (MAGIC), laser light can be replaced by long wavelength radiation in the radio-frequency (RF) regime, thus facilitating scalability.
Recent experimental results obtained using a freely programmable quantum computer (QC) based on MAGIC will be summarized first. In particular, we will report on the first proof-of-principle experimental demonstration of the deliberation process of a learning agent on a quantum computer. This experiment at the boundary between QIS and machine learning shows that decision making for reinforcement learning is sped up quadratically on a QC as compared to a classical agent. In addition, by varying the initial relative probabilities for obtaining a desired action over a wide range, we show that this experiment preserves these relative probabilities during the deliberation process.

RF-driven atomic ions and MAGIC, as used in these experiments, are a promising approach for realizing scalable quantum computing using interconnected modules containing quantum processors. Transport of trapped ions is a prerequisite for this and other scalable strategies for quantum computing with trapped ions. We have shown, by shuttling a single 171Yb+ ion 22 x 106 times and quantifying the coherence of its hyperfine qubit, that the quantum information stored in this qubit is preserved with a fidelity of 99.9994(+6 -7)% during transport of the ion over a distance of 250 μm.
Then we will report on the experimental progress in setting up and characterizing a novel type of surface ion trap for trapping 2D Coulomb crystals suitable for MAGIC. The electrode structures allow for varying the ion-surface separation, and the trap chip has resonant structures incorporated to enhance the RF magnetic fields to be used for all coherent operations on the hyperfine manifold of Yb+ ions. A variable magnetic field gradient is created using a combination of current-carrying elements and permanent magnets.

*Speaker

Gate-efficient simulation of molecular eigenstates on a quantum computer

Marc Ganzhorn * [1], Daniel Egger [1], Pauline Ollitrault [1], Panagiotis Barkoutsos [1], Gian Salis [1], Nikolaj Moll [1], Peter Mueller [1], Andreas Fuhrer [1], Marco Roth [2], Stefan Woerner [1], Ivano Tavernelli [1], Stefan Filipp [1]

[1] IBM Research – Switzerland
[2] Rheinisch-Westfälische Technische Hochschule Aachen – Germany

A key requirement to perform simulations of large quantum systems on current quantum processors is the design of quantum algorithms with short circuit depth. To achieve this, it is essential to realize a gate set that is tailored to the problem at hand and which can be directly implemented in hardware [1]. Here, we experimentally demonstrate that exchange-type gates are ideally suited for calculations in quantum chemistry [2]. We determine the energy spectrum of molecular hydrogen using a variational quantum eigensolver algorithm based on exchange-type gates in combination with a method from computational chemistry to compute the excited states. We utilize a parametrically driven tunable coupler [3]to realize exchange-type gates that are configurable in amplitude and phase on two fixed-frequency superconducting qubits. With gate fidelities around 95% we are able to compute the eigenstates within an accuracy of 50 mHartree on average, a limit set by the coherence time of the tunable coupler

*Speaker

The materials science of Josephson junctions: modelling their formation and electrical response from an atomistic point of view

Martin Cyster [1], Jackson Smith [1], Jesse Vaitkus [1], Nicolas Vogt [1], Salvy Russo [1], Jared Cole * [1]

[1] RMIT University [Melbourne]– Australia

The basis for superconducting qubits is the Josephson junction: a thin insulating barrier that separates two superconducting leads and thereby behaves as a tunnelling barrier. These junctions are the nonlinear circuit element inside superconducting quantum interference devices, microwave electronics, and superconducting quantum computers. The width of this barrier can be as thin as two nanometers and the electronic properties of such junctions are therefore strongly dependent on the morphology of the barrier, both at the interfaces of the superconducting leads and within the metal oxide itself.
We perform molecular dynamics simulations of the oxidation and deposition process, in order to develop atomistic models of aluminium-oxide tunnel junctions. Junction models constructed with this methodology are compared to models based on simulated annealing in which the characterisitics of the junction can be controlled systematically. We then perform a quantitative analysis of structural differences as a function of oxide density and the stoichiometric O/Al ratio in the barrier layer. By simulating the fabrication process, we aim to determine what characteristics naturally emerge from the fabrication process, and how they can be controlled by modifying the fabrication conditions.

To understand the electrical response of these model junctions, we have developed a new approach that captures the physics of the junction morphology using a three-dimensional electrostatic potential computed from molecular dynamics simulations. We calculate the normal resistance of a Josephson junction using the non-equilibrium Green's functions formalism and investigate the effect of changing the stoichiometry and oxide density of the insulating barrier.

Our results provide new insights into the influence of fabrication conditions on the electrical response of metal-oxide barriers and the resulting performance of quantum technologies constructed from them.

*Speaker

Quantum circuits with quantum control of causal orders

Cyril Branciard * [1]

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A standard model used to describe the functioning of a quantum computer is that of quantum circuits. In this model, a number of quantum systems (typically, qubits) undergo a number of individual or joint quantum operations, in a well-defined order. It has been realised recently, however, that quantum mechanics also allows for more general quantum circuits, where not only the quantum systems can be put in a superposition, or can be entangled, but where also the causal order in which the operations are applied can be indefinite and subject to quantum effects.
A canonical example is known as the "quantum switch", where the state of a control qubit commands (in a coherent manner) the order in which two operations are applied on a target system. The quantum switch was recently realised experimentally by several groups. Remarkably, it was shown to constitute a truly new resource for quantum information processing, allowing one to realise new tasks that are impossible for causally ordered quantum circuits-i.e., for standard quantum computers-or to perform certain tasks more efficiently.
In this talk I first propose to review the recent activity in this very lively research area, which investigates new types of quantum processes, based on new types of quantum causal structures. I will then present a new class of quantum circuits with quantum control of causal orders, beyond the basic example of the quantum switch, and investigate their applications for quantum information processing.

*Speaker

Chapter 3

Tuesday - 14:00-15:45 : Simulation - 1 (upper room)

OTOCs and SPT invariants from statistical correlations of randomized measurements

Andreas Elben * [2,1], Benoit Vermersch [1,2], Lukas Sieberer [1,2], Jinlong Yu [1,2], Guanyu Zhu [5], Norman Yao [3,4], Mohammad Hafezi [5], Peter Zoller [1,2]

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[4] Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley – United States
[5] JQI – University of Maryland, Maryland – United States

Recently, statistical correlations of randomized measurements have emerged as a new tool to probe properties of many-body quantum states beyond standard observables. Here, I focus on locally randomized measurements in spin models, implemented by the application of local random unitaries and a subsequent measurement in a fixed basis. After a general introduction, I will discuss two applications: First, I'll present a measurement protocol to measure out-of-time ordered correlation functions (OTOCs), without the necessity of implementing time reversed operations or ancilla degrees of freedom. Secondly, I'll show how the same tools can be used to access topological invariants of symmetry protected topological (SPT) phases in one-dimensional spin systems. Concentrating on invariants arising from inversion and time-reversal symmetry, which cannot be accessed using traditional string order parameters, I'll discuss explicit measurement protocols, and present examples in the context of the SHH model.

*Speaker

Coherence effects in Atomtronics circuits

Luigi Amico * [1]

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Atomtronics is an emerging field seeking to realize atomic circuits for quantum technology, exploiting ultra-cold atoms manipulated in micro-magnetic or laser-generated micro-optical circuits. Indeed, several atomtronic circuits on small and medium size scale have been recently realized experimentally. Important chapters in mesoscopic physics, like persistent currents in ring shaped structures, transport through quantum dots and more complex terminals, quantum phase slips etc. could be explored with an enhanced flexibility and control. In this talk, I will give a brief overview of the field. In particular, I will be focusing on maybe the simplest instance of atomtronic circuit: ultracold-atoms in ring-shaped potentials and pierced by an effective magnetic flux and attached to leads.

*Speaker

Hypersonic matterwave guiding for atom-interferometry

Saurabh Pandey , Hector Mas , Giannis Drougakis , Premjith Thekkeppatt , Georgios Vasilakis , Konstantinos Poulios , Wolf Von Klitzing * [1]

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Trapped atom-interferometry and atomtronics carry the promise of vastly increased sensitivity for fundamental and practical measurements. The main obstacle to fulfilling this promise so far is the lack of coherent transport of matterwaves and Bose-Einstein condensates (BEC) over macroscopic distances in non-trivial geometries. Any roughness of a wavguide, e.g. due to corrugations in the current carrying wires or speckles in optical patterns, couples the forward motion of the atoms to the transverse degrees of freedom, thus destroying the internal and external coherence of any traveling BEC. In recent years, we have developed magnetic time-averaged adiabatic potentials as a candidate for ultra-smooth waveguides. Here, we use these potentials to demonstrate for the first time an accelerator ring and waveguide for neutral atoms capable of rapid acceleration and coherence-preserving transport of ultracold atomic clouds and BECs. We accelerate the BECs to speeds up to hypersonic velocities, i.e. 16x their velocity of sound, and transport them in ultra-smooth magnetic waveguide rings over distances of up to 40 cm whilst completely preserving their internal coherence.

*Speaker

Exciton and charge transport via cavity-mediated long-range interactions

Guido Pupillo * [1]

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Strong light-matter interactions are playing an increasingly crucial role in the understanding and engineering of new states of matter with relevance to the fields of quantum optics, solid state physics and material science. Recent experiments with molecular semiconductors have shown that charge conductivity can be dramatically enhanced by coupling intra-molecular electronic transitions to the bosonic field of a cavity or of a plasmonic structure prepared in its vacuum state, even at room temperature [1]. In this talk, we discuss proof-of-principle models for charge and exciton transport where light-matter hybridization enabled by long-range cavity mediated interactions provides an enhancement of conductivity in the steady-state. We discuss the roles of disorder and finite electronic band-width in the light-matter dressing and current enhancement, which may reach orders of magnitude under experimenally relevant conditions [2,3]. We conclude with a discussion of open questions and opportunities in the field of vacuum-induced quantum materials.
References

[1]E. Orgiu *et al.*, Nature Materials **14**, 1123 (2015)
[2]D. Hagenmuller, J. Schachenmayer, S. Schutz, C. Genes, and G. Pupillo, Phys. Rev. Lett. **119**, 223601 (2107)
[3]D. Hagenmuller, S. Schutz, J. Schachenmayer, C. Genes, and G. Pupillo, Phys. Rev. B **97**, 205303 (2018)

*Speaker

Quantum Frequency Comb for Quantum Complex Networks

Valentina Parigi * [1]

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We show experimental procedures based on optical frequency combs and parametric processes able to produce quantum states of light involving large number of modes in the frequency and time domain. The protocols, along with mode selective and multimode homodyne measurements, allow for the implementation of reconfigurable entanglement connections between the involved modes. This can be exploited for fabricating entanglement structures with regular geometry as cluster states [1], which are considered a universal resource for continuous variables measurement-based quantum computing.
Also graphs with more complex topology: recently, quantum complex networks, i.e. collections of quantum systems arranged in a non-regular topology, have been explored leading to significant progress in a multitude of diverse contexts including, e.g., quantum transport, open quantum systems, quantum communication, extreme violation of local realism, and quantum gravity theories. We demonstrated that our strategy allows for deterministic implementation of networks with all-to all connection and full reconfigurability [2].

Additional non-Gaussian operations are necessaries to reach a form of quantum advantage in this scenario; a coherent-mode dependent single photon subtraction has been recently demonstrated in our setups. When appliedto the graph structure a special entanglement [3]properties appear, and the non-Gaussian features are spreadout with particular geometrical properties [4]. Moreover, the merging of non-Gaussian operations and complexnetwork structures disclose peculiar properties of the quantum states, which can also be investigated to simulatequantum transport. Finally, coherent single-photon subtraction on Gaussian multimode quantum states canbe exploited as a high-dimensional encoding, which is suitable for mapping arbitrary classical data in quantummechanical form [5].

[1]Y. Cai, et al. Nat. Comm. 8, 15645 (2017)
[2]J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps and V. Parigi, New Journal of Phys. 20, 053024 (2018).
[3]M. Walschaers, C. Fabre, V. Parigi and N. Treps, Phys. Rev. Lett. 119, 183601 (2017).
[4]M. Walschaers, S. Sarkar, V. Parigi, and N. Treps, Phys. Rev. Lett. 121, 220501(2018)
[5]F. Arzani, A. Ferraro, and V. Parigi, arXiv:1811.09263

*Speaker

Sample complexity of device-independently certified "quantum supremacy"

Dominik Hangleiter [1], Martin Kliesch * [2], Jens Eisert [1], Christian Gogolin [3,4]

[1] Freie Universität Berlin – Germany
[2] Heinrich Heine University Düsseldorf – Germany
[3] Institut de Ciencies Fotoniques [Barcelona]– Spain
[4] Xanadu [Toronto]– Canada

Results on the hardness of approximate sampling are seen as important stepping stones towards a convincing demonstration of the superior computational power of quantum devices. The most prominent suggestions for such experiments include boson sampling, IQP circuit sampling, and universal random circuit sampling. A key challenge for any such demonstration is to certify the correct implementation. For all these examples, and in fact for all sufficiently flat distributions, we show that any non-interactive certification from classical samples and a description of the target distribution requires exponentially many uses of the device. It is an ironic twist of our results that the same property that is a central ingredient for the approximate hardness results, prohibits sample-efficient certification: namely, that the sampling distributions, as random variables depending on the random unitaries defining the problem instances, have small second moments.

*Speaker

Probing the influence of many-body fluctuations on Cooper pair tunneling using circuit QED

Sebastien Leger * [1], Javier Puertas-Martinez [2], Luca Planat [3], Karthik Bharadwaj [4], Rémy Dassonneville [5], Vladimir Milchakov [5], Nicolas Roch [6], Jovian Delaforce [7], Farshad Foroughi [2], Olivier Buisson [5], Naud Cécile , Wiebke Hasch-Guichard [3], Serge Florens [8], Izak Snyman

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[2] Institut Néel (NEEL) – Université Grenoble Alpes [Saint Martin dH́ères]– 25 rue des Martyrs - BP 166 38042 GRENOBLE CEDEX 9, France
[3] Institut Neél – Centre National de la Recherche Scientifique - CNRS, Université Joseph Fourié – France
[4] Institut Néel (NEEL) – Université Grenoble Alpes [Saint Martin dH́ères], Centre National de la Recherche Scientifique : UPR2940 – 25 rue des Martyrs - BP 166 38042 GRENOBLE CEDEX 9, France
[5] institut neel – CNRS : UPR2940 – grenoble, France
[6] CNRS and Université Grenoble Alpes, Institut Néel – CNRS : UPR2940 – 38042 Grenoble, France, France
[7] Institut Néel, UGA-CNRS – CNRS : UPR2940 – 25 rue des Martyrs BP 166 38042 Grenoble cedex 9, France
[8] Institut Néel (NEEL) – CNRS : UPR2940 – 25 rue des Martyrs - BP 166 38042 GRENOBLE CEDEX 9, France

Because of the value of the hyperfine constant (_˜ 1/137) observing many body effects in light-matter interaction is challenging. Reaching this regime is now possible using the tools of circuit Quantum ElectroDynamics (cQED) [1,2].
In this work we investigate the interactions between the plasma modes propagating in arrays of more than 4000 SQUIDs (which simulate the light) and a small Josephson junction (the matter). The first effect of these modes is to broaden the energy level of the Josephson junction [1,2]. More interestingly they can also induce strong phase fluctuations across the junction, which directly affects the Cooper pair tunneling. We will present our on-going experimental efforts aimed at observing this purely quantum many-body effect.

[1]P. Forn-Díaz, et al. ”Ultrastrong coupling of a single artificial atom to an electromagnetic continuum in the nonperturbative regime,” Nature Physics, 13(1), 39–43 (2016).
[2]J. Puertas Martínez, S.Léger, et al. ”A tunable Josephson platform to explore many-body quantum optics in circuit-QED,” arXiv:1802.00633.

*Speaker

Chapter 4

Wednesday - 14:00-16:00 : BSCC - 2 (Platine)

New single photon emitters in diamond based on group IV impurities

Sviatoslav Ditalia Tchernij * [1], Paolo Olivero [1], Jacopo Forneris Et Al. [2], Jan Meijer Et Al. [3], Milko Jakšić, Et Al., [4], Marco Genovese, Et Al., [5]

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[2] Istituto Nazionale di Fisica Nucleare (INFN) – Italy
[3] Department of Nuclear Solid State Physics, University of Leipzig – Germany
[4] Laboratory for Ion Beam Interactions, Ruder Bošković Institute, Zagreb – Croatia
[5] Istituto Nazionale di Ricerca Metrologica (INRiM) – Italy

Diamond is a promising platform for the development of technological applications in quantum optics and photonics. The quest for new color centers with optimal photo-physical properties has led in recent years to the search for novel impurity-related defects in this material, with the purpose of enabling the fabrication of specific luminescent defects upon a controlled ion implantation process. Particularly group IV impurities related color centers like Si-V and the recently discovered Ge-V have attracted a broad interest in the last years thanks to their short lifetimes and narrow spectral emission lines. In this contribution, we report on our recent progresses at the fabrication and characterization of novel classes of quantum emitters in single-crystalline diamond based on Sn [1]and Pb [2]color centers. These color centers share many of their opto-physical properties with the other group IV impurities, such as a short lifetime and a narrow spectral emission, while being characterized by a higher brightness. The attribution of the newly discovered optical centers to Sn- and Pb-containing defects was performed through the correlation of their photoluminescence (PL) intensity with the implantation fluence. Hanbury-Brown&Twiss interferometry measurements confirmed the single photon emission from isolated defects located in ion implanted areas. These results represent a significant step towards completing the interpretational framework on the optical activity of diamond defects related to group IV impurities. Future studies on these defects properties at the single-photon emitter level could lead to appealing perspectives in the fields of quantum information processing and quantum sensing. Furthermore, from a fundamental point of view, the mapping and thorough understanding of a general pattern in the opto-physical properties of color centers associated with impurities of the whole group IV could provide an important reference for the study of defects related to other chemical species.
[1]S. Ditalia Tchernij *et al.*, *ACS Photonics*, vol. 4, no. 10, pp. 2580–2586, Oct. 2017.
[2]S. Ditalia Tchernij *et al.*, *ACS Photonics*, acsphotonics.8b01013, Nov. 2018.

*Speaker

Deterministic Creation and Spins in Quantum Emitters in Atomically Thin Semiconductors

Alejandro Montblanch * [1], Matteo Barbone [1], Carmen Palacios-Berraquero [1], Dhiren Kara [1], Pawel Latawiec [2], Marko Loncar [2], Andrea Ferrari [1], Mete Atatüre [1]

[1] University of Cambridge – United Kingdom
[2] Harvard University – United States

Quantum emitters (QEs) have been observed in tungsten diselenide (WSe2), a member of the 2-dimensional transition metal dichalcogenides (2D-TMDs). This is particularly exciting since the 2D nature of TMDs makes them ideal for interfacing with photonic structures and building optoelectronic devices in the form of van der Waals heterostructures. TMDs also offer dangling-bond free surfaces, removing the issue of charge noise and traps faced by close-to-surface QEs in bulk crystals. We have created QE arrays with nanoscale strain engineering[1]. This is essential for scalable technology and sheds light on their as yet unknown origin. Further we have implemented a 2D quantum light emitting diode design and demonstrated electrically-driven single photon emission in both WSe2 and WS2 [2]. This demonstrates that quantum emission is ubiquitous to the 2D-TMD family and available at different emission wavelengths across the visible spectrum. I will finally discuss our current efforts to charge a QE with an electron or hole, which would provide a long-lived spin state for use as a qubit.

[1]C. Palacios-Berraquero, D. M. Kara, A. R.-P. Montblanch, Matteo Barbone et al, Large-scale quantum-emitter arrays in atomically thin semiconductors. Nat Commun. 8, 15093, doi: 10.1038/ncomms15093 (2017).
[2]C. Palacios-Berraquero, Matteo Barbone et al. Atomically thin quantum light-emitting diodes. Nat. Commun. 7, 12978 doi: 10.1038/ncomms12978 (2016).

*Speaker

Nanomaterials with optically addressable spins for quantum technologies

Alexandre Fossati [1], Mary De Feudis [2], Shuping Liu [1], Diana Serrano [1], Alban Ferrier [1], Ovidiu Brinza [2], Jocelyn Achard [2], Alexandre Tallaire [1], Philippe Goldner * [1]

[1] Institut de Recherche de Chimie Paris – Chimie ParisTech, CNRS, PSL University – France
[2] Laboratoire des Sciences des Procédés et des Matériaux – université Paris 13, Institut Galilée, Centre National de la Recherche Scientifique – France

Nanoscale systems offer new functionalities for spin-based quantum technologies, like single spin control and detection, or extremely localized sensing of magnetic and electric fields. The ability to couple centers with light is an attractive feature for these systems for interfacing with photonic qubits, creating light matter entanglement, fast processing and efficient state read-out [1]. Two of the most promising systems in this field are rare earth doped crystals and color centers in diamond. As bulk materials, they have shown exceptional properties, especially in terms of coherence lifetimes [2,3], a key property that has enabled impressive demonstrations in quantum sensing, storage, and processing. Preserving coherence lifetimes at the nanoscale is however highly challenging, because new sources of dephasing arise, related to the high surface to volume ratio, as well as impurities and additional strain introduced during the synthesis. New and highly controlled ways of obtaining these materials at the nanoscale are therefore needed. In this paper, we will present recent results obtained in our groups on rare earth doped wet chemistry nanoparticles, in which optical linewidths in the 10s of kHz range and ms long spin coherence lifetimes have been shown [4,5], and high purity CVD nano-diamonds containing NV, SiV and GeV centers. Dephasing processes will be discussed, as well as strategies to decrease them, in the light of the common and specific properties of these two nanoscale systems.

This work is supported by the Quantum Technology Flagship projects Square and Asteriqs, and the FET Open project NanOQTech.

References:

[1]D. D. Awschalom et al., "Quantum technologies with optically interfaced solid-state spins," Nat. Photonics **12**, 1–12 (2018).
[2]M. Zhong et al., "Optically addressable nuclear spins in a solid with a six-hour coherence time," Nature **517**, 177–180 (2015).
[3]G. Balasubramanian et al., "Ultralong spin coherence time in isotopically engineered diamond," Nat. Mater. **8**, 383–387 (2009).
[4]J. G. Bartholomew et al., "Optical Line Width Broadening Mechanisms at the 10 kHz Level in Eu3+:Y2O3 Nanoparticles," Nano. Lett. **17**, 778–787 (2017).
[5]D. Serrano et al., "All-optical control of long-lived nuclear spins in rare-earth doped nanoparticles," Nat. Commun. **9**, 2127 (2018).

*Speaker

Two-dimensional quantum materials and devices for scalable integrated photonic circuits

Dmitri Efetov * [1], Frank Koppens [1], Kostya Novoselov [2], Volodya Falko [2], Andrea Ferrari [3], Mete Atatüre [3], Gabriele Bulgarini [4], Maco Romagnoli [5]

[1] ICFO- The Institute of Photonic Sciences – Spain
[2] University of Manchester – United Kingdom
[3] Cambridge University – United Kingdom
[4] Single Quantum – Netherlands
[5] CNIT – Italy

This talk gives a progress report on the project 2D-SIPC. The project aims at developing scalable quantum networks, based on photonic chip integration of novel 2D material quantum devices, with the main goal to demonstrate all-optical on-chip quantum processing. The recent demonstration of effortless integration of 2D materials onto photonics and CMOS platforms will result in a breakthrough in the development of on-chip quantum networks. 2D-SIPC will take full advantage of the huge variety of 2D materials and heterostructures and prototype novel quantum devices with revolutionary functionalities. In particular, we will develop electrically driven and entangled single photon emitters, broadband and high temperature single photon detectors, ultra-fast waveguide integrated optical modulators and non-linear gates. To pave the way to scalable networks, 2D-SIPC will develop large scale growth techniques of the most promising 2D materials. With this unique combination of features 2D-SIPC will allow the first demonstration of on-chip optical quantum processing, a key milestone for many quantum network concepts, such as extended secure quantum communication, scaling up of quantum computers and simulators, and novel quantum sensing applications with entangled photons. In particular, as these topics cover all four Quantum Technology pillars of the Quantum Flagship, our proposal makes a strong strategic link to each one of them. Beyond the 2D-SIPC platform, each developed component will be exploited in such distant fields as biological and medical imaging, radio-astronomy and environmental monitoring. The 2D-SIPC consortium includes four academic and one industrial partner with a high degree of complementarity that are at the forefronts of their fields, including single photon detection (ICFO), theory and fabrication of 2D materials and their heterostructures (UNIMAN), single photon emission (UCAM), chip based photonic circuits (CNIT) and commercial single photon detection, single photon emission and packaging (SQ).

*Speaker

Scalable Rare Earth Ion Quantum Computing Nodes (SQUARE)

David Hunger * [1]

[1] Karlsruhe Institute of Technology – Germany

Quantum technologies rely on materials that offer the central resource of quantum coherence, that allow one to control this resource and to harness interactions to create entanglement. Rare earth ions (REI) doped into solids have an outstanding potential in this context and could serve as a scalable, multi-functional quantum material. REI provide a unique physical system enabling a quantum register with a large number of qubits, strong dipolar interactions between the qubits allowing fast quantum gates, and coupling to optical photons – including telecom wavelengths – opening the door to connect quantum processors in a quantum network. The flagship project SQUARE aims at establishing individually addressable rare earth ions as a fundamental building block of a quantum computer, and to overcome the main roadblocks on the way towards scalable quantum hardware. The goal is to realize the basic elements of a multifunctional quantum processor node, where multiple qubits can be used for quantum storage, quantum gates, and for coherent spin-photon quantum state mapping. Novel schemes and protocols targeting a scalable architecture will be developed. The central photonic elements that enable efficient single ion addressing will be engineered into deployable technologies.

*Speaker

Project S2QUIP: Scalable Two-Dimensional Quantum Integrated Photonics

Klaus Jöns * [1]

[1] KTH Stockholm – Sweden

S2QUIP will introduce a paradigm shift in the development of scalable cost-effective integrated-chip quantum light sources. Scalable quantum light sources are of significant importance for the future quantum photonics technology applications. Current technologies still lack on-chip scalability due to the cumbersome integration of quantum light sources (e.g. quantum dots or crystal defects) that require a high-quality bulk matrix environment to operate. Here, S2QUIP aims to utilize atomically flat two-dimensional (2D) layered semiconductors to provide maximum flexibility for incorporation of quantum light sources into scalable photonic chip architectures using surface processing instead of bulk processing. Single and entangled photons will be deterministically generated using 2D semiconductors and efficiently coupled to on-chip cavities and multiplexed using integrated waveguides, switches, and beam-splitters. This approach will allow the demonstration of useful entangled photon states in a deterministic and scalable fashion that far surpasses the state-of-the-art using bulk semiconductors and optics. S2QUIP's ambitious goal is to achieve 20 multiplexed quantum light sources that can fulfill the long-awaited expectation of scalable on-chip quantum light sources for numerous quantum technologies (e.g., large-scale quantum computation, communication and sensing).

*Speaker

Optical nanofibre mediated light interactions with cold Rb atoms

Síle Nic Chormaic * [1], Thomas Nieddu [1], Krishnapriya S Rajasree [1], Ratnesh K Gupta [1], Tridib Ray [1], Kristoffer Karlsson [1], Jesse Everett [1]

[1] Okinawa Institute of Science and Technology – Japan

Optical nanofibres have already demonstrated their usefulness for the development of hybrid atom:photon quantum systems. Their main feature is the large evanescent field that extends into the medium beyond the fibre surface. The light field has a high intensity and a steep gradient even if low light powers are used, enabling the study of interesting phenonema in light-matter interactions that would otherwise be hard to access. This includes aspects such as nonlinear behaviour in atomic media, studies on dipole fobidden atomic transitions, fibre-based dipole traps, etc. Here, we'll present some of our recent work on optical nanofibres both as light propagation tools and as interface devices for cold atoms. This will include our method of determining the polarization at the fibre waist using a crossed-fibre setup, demonstration of one-colour, two-photon excitations in cold Rb leading to Autler-Townes splitting, the formation of cold Rb Rydberg atoms around the nanofibre, and, finally, modal identification at the fibre waist by determining the fibre's transfer matrix. Overall, the range of topics that can be studied with such a simple optical device will be emphasised. This last aspect sholud allow us to experimentally probe quadrupole transitions within atomic media and explore the transfer of orbital angular momentum to different decay paths within Rb.

*Speaker

Project MicroQC (Microwave driven ion trap quantum computation)

Nikolay Vitanov * [1], Alex Retzker [2], Christian Ospelkaus [3], Christof Wunderlich [4], Winfried Hensinger [5]

[1] Sofia University – Bulgaria
[2] The Hebrew University of Jerusalem – Israel
[3] Leibniz Universitaet Hannover – Germany
[4] Universität Siegen [Siegen]– Germany
[5] University of Sussex – United Kingdom

Progress report of the Flagship project MicroQC.

*Speaker

Chapter 5

Wednesday - 14:00-16:00 : Computing - 2 (Upper room)

T-count optimization of quantum circuits using graph-theoretical rewriting of ZX-diagrams

John Van De Wetering * [1], Aleks Kissinger [1]

[1] Radboud university [Nijmegen]– Netherlands

Most fault-tolerant architectures for quantum computers allow fast execution of Clifford gates, so that the majority of their resources is spend on implementing non-Clifford gates, specifically T-gates. It is therefore desirable to find optimizations of quantum circuits where the T-count is as low as possible. While the field of T-count optimization has seen a variety of approaches in recent years, what they all have in common is that they restrict themselves to the circuit model, and hence never stray from unitary quantum theory.
In this talk we will demonstrate a wildly different approach, by writing quantum circuits as ZX-diagrams, a type of tensor network consisting of non-unitary generators, called Z- and X-spiders, which come with a set of rewrite rules known as the ZX-calculus. It has been shown that the ZX-calculus is complete for Clifford circuits, meaning that two Clifford circuits are equal if and only if one can be rewritten into the other by the rules of the ZX-calculus. There are also various known additional rewrite rules that make the calculus complete for Clifford+T or all circuits. We use a specific set of rewrite rules based on the graph-theoretic notions of local complementation and pivoting that always terminate in finite time, in addition to a procedure of gadgetization that rewrites T-gates into a form more amenable to simplification. The result is a ZX-diagram with a T-count that in most cases matches, and in some cases surpasses the best known state-of-the-art T-count (e.g. in one particular case we achieve a T-count equal to 50% of the previous best-known). The diagram produced by our rewrites is however not circuit-like. We use techniques based on the notion of cut-rank to cut our diagram into pieces that do resemble a circuit, and in this way we can extract a circuit from the ZX-diagram. The resulting circuit is not optimized for general gate-count, but post-processing with some trivial circuit identities followed by phase-polynomial optimization gives competitive values for CNOT-count and Hadamard-count.

We will present the theory behind our simplification strategy and give a demonstration of the open source Python library in which we have implemented it: PyZX. The reader is also invited to watch our short demonstration video about PyZX, available at
https://www.youtube.com/watch?v=iC-KVdB8pf0

*Speaker

An Open Superconducting Quantum Computer

Frank Wilhelm-Mauch * [1], Jonas Bylander [2], Per Delsing [2], Christopher Eichler [3], David Gunnarsson [4], Juha Hassel [5], Göran Johansson [6], Lucas Lamata [7], Adrian Messmer [8], Kristel Michielsen [9], Mika Prunnila [5], Leif Roschier [4], Enrique Solano [10,11], Göran Wendin [12]

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[2] Chalmers University of Technology – Sweden
[3] ETH Zurich – Zurich, Switzerland
[4] Bluefors Oy, Helsinki, Finland – Finland
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[6] Department of Microtechnology and Nanoscience - MC2 – Chalmers University of Technology S-412 96 Göteborg, Sweden
[7] Department of Physical Chemistry, University of the Basque Country (UPV/EHU) – Apartado 644, E-48080 Bilbao, Spain
[8] Zurich Instruments AG, Zurich, Switzerland – Switzerland
[9] Jülich Supercomputing Centre – Germany
[10] Department of Physical Chemistry, University of the Basque Country – Spain
[11] University of Shanghai [Shanghai]– China
[12] Department of Microtechnology and Nanoscience - MC2 – Sweden

The OpenSuperQ consortium aims at building a quantum computer, based on superconducting integrated circuits with 50 to 100 qubits, that is large enough not to be simulable on current classical supercomputers. It is going to use elements that are established at few-qubit scale, such as 2D-transmon qubits, parametric amplifiers, dilution refrigerators and room-temperature electronics, with scaling and integration posing a whole new challenge. In this talk, I am going to describe progress towards reliable fabrication of high-coherence qubits, three-dimensional integration and packaging, multiplexed readout, cryogenics, high-fidelity quantum control, application development, and benchmarking. A whole new challenge lies in the vertical integration of hard- and software, comprising the immediate control electronics, the user interface, and the connecting middleware infrastructure. OpenSuperQ engages with a large community of users and scientists and is exploring first use cases for its hardware.

*Speaker

Quantum Lattice Enumeration

Yixin Shen * [1], Phong Nguyen [2,3,4], Yoshinori Aono [5]

[1] Université Paris Diderot - Paris 7 – Institut de recherche en informatique fondamentale – France
[2] Japanese French Laboratory for Informatics – Japan
[3] Inria de Paris – Institut National de Recherche en Informatique et en Automatique – France
[4] The University of Tokyo – Japan
[5] National Institute for Information and Communications Technology – Japan

Enumeration is a fundamental lattice algorithm. We show how to speed up enumeration on a quantum computer, which affects the security estimates of several lattice-based submissions to NIST: if T is the number of operations of enumeration, our quantum enumeration runs in roughly sqrt{T} operations. This applies to the two most efficient forms of enumeration known in the extreme pruning setting: cylinder pruning but also discrete pruning introduced at Eurocrypt '17. Our results are based on recent quantum tree algorithms by Montanaro and Ambainis- Kokainis.

The discrete pruning case requires a crucial tweak: we modify the preprocessing so that the running time can be rigorously proved to be essentially optimal, which was the main open problem in discrete pruning.

*Speaker

Application on LHC High Energy Physic data analysis with IBM Quantum Computing

Sau Lan Wu [1], Jay Chan [1], Wen Guan * [1], Shaojun Sun [1], Alex Wang [1], Chen Zhou [1], Federico Carminati [2], Ivano Tavernelli [3], Stefan Wörner [3]

[1] University of Wisconsin Madison – United States
[2] CERN openlab – Switzerland
[3] IBM Research Zürich – Switzerland

We will present our experiences and preliminary studies on LHC high energy physics data analysis with quantum simulators and IBM quantum computer hardware using IBM Qiskit. The performance is compared with the results using a classical machine learning method applied to a physics process in Higgs-coupling-to–two-top-quarks as an example. This work is a collaboration between University of Wisconsin-Madison, CERN openlab and IBM.

*Speaker

”Training” parameterized quantum circuits

Dirk Oliver Theis * [1], Gil Vidal Gil Vidal [1], Bahman Ghandchi [2], Kaveh Khoshkhah [2]

[1] University of Tartu – Estonia
[2] Ketita Labs Ltd – Estonia

Parameterized quantum circuits (PQCs) are a promising approach to exploiting near-term noisy quantum computers. The parameters in the PQCs are modified iteratively to arrive at a – in some sense – optimal parameter setting, a process unfortunately referred to as ”training” the PQC. The term PQC includes the quantum circuits used in the Variational Quantum Eigensolver, but also those in approaches to combinatorial optimization [N. Moll et al. ”Quantum optimization using variational algorithms on near-term quantum devices”]and machine learning [E. Farhi & H. Neven ”Classification with quantum neural networks on near term processors”]on NISQ computers.
Training PQCs is fraught with challenges, some of which this talk will address:

The typical approach to training PQCs is (some version of) gradient descent. Directional derivatives can be estimated by estimating a small number of expectation values of the original PQC [K. Mitarai et al. ”Quantum circuit learning”]; extending results in [M. Schuld et al. ”Evaluating analytic gradients on quantum hardware”], we show how this can be done whenever the eigenvalues of the Hamiltonians are evenly spaced.

It has been observed [J. McClean et al. ”Barren plateaus in quantum neural network training landscapes”]that, typically, the gradients are exponentially (in the number of qubits) small in all but an exponentially small fraction of the parameter space – rendering optimization basically impossible. We study a mathematical abstraction of the functions computed by Mitarai et al.’s type of PQCs using analytic and complexity theoretic tools. On the one hand, we derive conditions for when optimization is possible; on the other hand, we give results for when training requires exponentially many estimations of expectation values of the quantum circuit. (At this point in time, we cannot yet translate these results back from the math into designs of PQCs, i.e., we are currently not able to tell from the design of the PQC whether it is ”trainable” or not.)
Finally, we give an outlook on how the effect of quantum noise in the training of PQCs might be mitigated.

*Speaker

Flight Gate Assignment with a Quantum Annealer

Tobias Stollenwerk * [1], Elisabeth Lobe [1]

[1] German Aerospace Center – Germany

Optimal flight gate assignment is a highly relevant optimization problem from airport management.
Among others, an important goal is the minimization of the total transit time of the passengers.
The corresponding objective function is quadratic in the binary decision variables encoding the flight-to-gate assignment.
Hence, it is a quadratic assignment problem being hard to solve in general.
In this work we investigate the solvability of this problem with a D-Wave quantum annealer.
These machines are optimizers for quadratic unconstrained optimization problems (QUBO).
Therefore the flight gate assignment problem seems to be well suited for these machines.
We use real world data from a mid-sized German airport as well as simulation based data to extract typical instances small enough to be amenable to the D-Wave machine.
In order to mitigate precision problems, we employ bin packing on the passenger numbers to reduce the precision requirements of the extracted instances.
We find that, for the instances we investigated, the bin packing has little effect on the solution quality.
Hence, we were able to solve small problem instances extracted from real data with the D-Wave 2000Q quantum annealer.

*Speaker

Quantum Annealing Tabu Search

Enrico Blanzieri * [1], Davide Pastorello *

[2,3]

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[3] Trento Institute for Fundamental Physics and Applications – Italy

Quantum Annealing is a type of heuristic search to solve optimization problems. The solution of a given problem corresponds to the ground state of a quantum system, then a time-evolution of the system is set in order to reach the ground state with high probability. The quantum advantage w.r.t. classical optimization is essentially given by the tunnel effect for escaping the local minima of the solutions landscape.
The typical hardware architecture of a quantum annealer is given by a network of qubits arranged on the vertices of a graph whose edges represent the interactions between neighbors. Since the graphs of the existing physical machines are sparse, the embedding of an optimization problem into the annealer architecture may be computationally hard with deleterious effects on performances.

We propose a novel approach based on the hybrid paradigm that is a general strategy where repeated calls of a quantum annealer are carried out within a classical algorithm as an alternative to the direct reduction of an optimization problem into the sparse annealer graph. Our approach is based on an iterative structure where the representation of an objective function into the annealer architecture in not a priori fixed but evolves and already-visited solutions are penalized. In particular we discuss how to implement a tabu search inside a quantum annealer. Candidate solutions are generated by quantum annealing and the iterative initializations of the machine are designed to energetically discourage some solutions. We show that the tabu strategy is completely realized on the quantum side of the scheme by the definition and the updating of a matrix to deform the Hamiltonian of the qubits network.
Once illustrated the proposed hybrid quantum-classical procedure to avoid the direct reduction of problem instances into the sparse annealer graph, we prove the convergence of our algorithm to a global optima in the case of quadratic unconstrained binary problems.

*Speaker

Project AQTION: Advanced quantum computing with trapped ions

Thomas Monz * [1]

[1] Institute for Experimental Physics, University of Innsbruck – Austria

This project focuses on scalability, availability, and applicability aspects of trapped-ion quantum computers, tackling the transition from current laboratory-based experiments to industry-grade quantum computing technologies. This project will provide the technological framework for quantum computers to solve real-world problems inaccessible to current classical computers. Taking advantage of the unrivalled low error rates of operations available in trapped-ion quantum processors today, we will develop a fully connected 50-qubit device, allowing the implementation of calculations that are out of the reach of classical computers. The system will enable straightforward high-level user access via a robust hardware and software stack, allowing remote execution of complex algorithms without hardware-specific knowledge. We will pave the way to large-scale and fault-tolerant quantum computing by introducing long-range connectivity via ion-shuttling between sub-processors and by establishing remote operations between quantum processors using photonic interconnects. These scalable techniques will make systems exceeding thousands of qubits possible, in combination with error correction and entanglement purification techniques. Within this project, we will combine these quantum information techniques with trap fabrication and packaging technologies which integrate optical and electronic components to achieve stable long-term operation in an industrial environment. These scientific and technological advances will provide a powerful platform to demonstrate trapped-ion quantum computers capable of solving problems of major commercial importance including computational problems in chemistry and machine learning.

*Speaker

Chapter 6

Wednesday - 14:00-16:00 : Communication - 1 (Auditorium)

Project QIA: Quantum Internet Alliance

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The future Quantum Internet will provide radically new internet applications by enabling quantum communication between any two points on Earth. The Quantum Internet Alliance (QIA) targets a Blueprint for a pan-European Quantum Internet by ground-breaking technological advances, culminating in the first experimental demonstration of a fully integrated network stack running on a multi-node quantum network.

QIA will push the frontier of technology in both end nodes (trapped ion qubits, diamond NV qubits, neutral atom qubits) and quantum repeaters (rare-earth-based memories, atomic gases, quantum dots) and demonstrate the first integration of both subsystems. We will achieve entanglement and teleportation across three and four remote quantum network nodes, thereby making the leap from simple point-to-point connections to the first multi-node networks. We will demonstrate the key enabling capabilities for memory-based quantum repeaters, resulting in proof-of-principle demonstrations of elementary long-distance repeater links in the real-world, including the longest such link worldwide.

Hand in hand with hardware development, we will realize a software stack that will provide fast, reactive control and allow arbitrary high-level applications to be realized in platform-independent software. QIA's industry partners examine real world use cases of application protocols and their hardware requirements. We will validate the full stack on a small Quantum Internet by performing an elementary secure delegated quantum computation in the cloud. We will validate the design of the Blueprint architecture by a large-scale simulation of a pan-European Quantum Internet using real world fibre data. Through synergy of leading industrial, academic and RTO partners, QIA's Blueprint will provide a targeted roadmap for the main Flagship phase and set the stage for a world-leading European Quantum Internet industry.

*Speaker

UNIQORN - Affordable Quantum Communication for Everyone: Revolutionizing the Quantum Ecosystem from Fabrication to Application

Hannes Hübel * [1], Harald Herrmann [2], Tobias Gering [3], Rui Santos [4], Philip Walther [5], Paraskevas Bakopoulos [6], Moritz Kleinert [7], Christos Kouloumentas [8], Gregor Weihs [9], Simone Tisa [10], Xaveer Leijtens [11], Igor Koltchanov [12], Franco Zappa [13], Emilio Hugues-Salas [14], Eleni Theodoropoulou [15], Xin Yin [16], Peppino Primiani [17]

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[13] Politecnico di Milano – Italy
[14] University of Bristol – United Kingdom
[15] COSMOTE Mobile Telecommunications S.A. – Greece
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[17] Cordon Electronics Italia Srl – Italy

Powerful quantum applications need powerful yet cost-effective components: Optical quantum communication is demanding challenging component specifications, which can quickly lead to a performance brick-wall when commercial off-the-shelf componentry is incorporated. At the same time the use of highly specialized, bulky and costly opto-electronics leads to capital expenditures that are prohibitive for end-user markets. UNIQORN's mission is therefore to provide the enabling photonic technology to accommodate quantum communication applications, by shoehorning complex systems, which are presently found on metre-size breadboards, into millimetre-size chips. These systems will not only reduce size and cost but will also bring improvements in terms of robustness and reproducibility.

During the 3-year lifetime, the project will develop the key components for quantum communication applications such as are used for quantum random number generation, quantum key distribution, one-time programs and quantum oblivious transfer. Component-wise, UNIQORN will leverage the monolithic integration potential of InP platform, the flexibility of polymer platforms and low-cost assembly techniques to develop quantum system-on-chip modules in a cheap, scalable and reproducible way. The InP integration will focus on small, weak coherent-pulse,

*Speaker

photon transmitters and on improved balanced receivers for detection of continuous variables quantum states. In addition, UNIQORN will deliver bright heralded, entangled and squeezed light sources based on a hybrid approach featuring non-linear crystals on a polymer matrix. Integration of CMOS SPADs will augment the polymer components.
Network-integration and system/application evaluations in real fibre networks will be enabled by quantum-aware software defined networking protocols and field trials in the live Smart-City demonstrator Bristol-is-Open.

Quantum Storage of Frequency-Multiplexed Heralded Single Photons

Dario Lago-Rivera * [1], Alessandro Seri [2], Andreas Lenhard [2], Giacomo Corrielli [3,4], Roberto Osellame [3,4], Margherita Mazzera [2], Hugues De Riedmatten [2,5]

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Quantum memories for light are important devices in quantum information, in particular for applications such as quantum networks and quantum repeaters. Multimode quantum memories able to store independently multiple modes would greatly help the scaling of quantum networks by decreasing the entanglement generation time between remote quantum nodes. Current research focuses mostly on time multiplexing in rare-earth doped crystals and in spatial multiplexing in atomic gases. Beyond these demonstrations, rare-earth doped crystals, thanks to their large inhomogeneous broadening, represent a unique quantum system which could also add another degree of freedom, the storage of multiple frequency modes. In this contribution, we report on the first demonstration of quantum storage of a frequency multiplexed single photon into a laser-written waveguide integrated in a praseodymium (Pr) crystal.

We use a cavity-enhanced spontaneous parametric down conversion source to generate frequency multiplexed photon pairs, with one photon in resonance with the transition of the Pr and the other at telecom wavelength.
We use the atomic frequency comb protocol to demonstrate storage of the multiplexed heralded single photon. We show that we can store the main part of its spectrum consisting of 15 modes. This leads to an increase of our count-rate by a factor 5.5 with respect to the single frequency mode storage. This high count rate allows us to make a detailed analysis of the multiplexed biphoton state after the storage. We study the non classicality of the stored photons after being stored for 3.5 us. The measured cross-correlation function violates the Cauchy-Schwarz classical bound, as well as the heralded autocorrelation of the stored photons. We show that we are able to increase the non classicality by lowering the pump power of the source.

Together with the 9 temporal modes, stored as an intrinsic property of the AFC protocol, we demonstrate the storage of more than 130 individual modes. The ability to combine several multiplexing capabilities in one system would open the door to the realization of massively multiplexed quantum memories.

*Speaker

Towards broadband optical spin-wave quantum memory

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Here we demonstrate a spin-wave storage realized in 171Yb3+:Y2SiO5 crystal, with storage times beyond a millisecond. For this we use simultaneously induced clock transitions for both microwave and optical domains, reaching coherence times of above 1 ms and 100 μs, respectively. This effect is due to the highly anisotropic hyperfine interaction, which makes each electronic-nuclear state an entangled Bell state at zero magnetic field. Using this effect we realize the atomic frequency comb protocol for storing optical excitation in long lived spin states. Large energy splittings lying in GHz range give the possibility to realize broadband light matter interface. These results represent a step towards realizing a long-lived, broadband and multimode solid-state quantum memory.

*Speaker

A Broadband Rb Vapor Cell Quantum Memory for Single Photons

Gianni Buser * [1], Janik Wolters [1], Roberto Mottola [1], Chris Müller [2], Tim Kroh [2], Richard Warburton [1], Oliver Benson [2], Philipp Treutlein [1]

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Quantum memories are an essential ingredient for quantum repeaters [1]. Further, through synchronization they can facilitate the generation of multiphoton states, which provides a realistic prospect of scaling optical quantum information processing experiments into a regime beyond the realm of classical simulation [2]. We implemented a broadband optical quantum memory with on-demand storage and retrieval in hot Rb vapor [3]. Operating on the Rb D1 line, this memory is suited for storing single photons emitted by GaAs droplet quantum dots [4]or by spontaneous parametric downconversion (SPDC) sources [5].
We report on our recent achievements with regards to this memory. We have reduced the readout noise farther below the single input photon equivalent ($\mu 1 \ll 1$) and increased the memory lifetime to μs. Additionally, we demonstrate storage of true single photons with a bandwidth > 100 MHz, generated by a SPDC source with 40 % heralding efficiency.

[1]N. Sangouard et al., Rev. Mod. Phys. **83**, 33 (2011).
[2]J. Nunn et al., Phys. Rev. Lett. **110**, 133601 (2013).
[3]J. Wolters, et al., Phys. Rev. Lett. **119**, 060502 (2017).
[4]J.-P. Jahn, et al. Phys. Rev. B **92**, 245439 (2015).
[5]A. Ahlrichs et al., Appl. Phys. Lett. **108**, 021111 (2016).

*Speaker

Diamond Qubits in Nanocavity Spin-Photon Interfaces for Quantum Communication

Tim Schröder * [1], Sara Mouradian [2], Michael Walsh [2,3], Noel Wan [2], Matt Trusheim [2], Erik Bersin [2], Dirk Englund [2]

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[3] ITER Organization (ITER) – ITER – Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

A central aim of quantum information processing is the efficient entanglement of multiple stationary quantum memories via photons to realize scalable quantum networks. Recently, quantum entanglement and distillation as well as teleportation have been shown between two nitrogen-vacancy (NV) memories, but scaling to larger networks requires more efficient spin-photon interfaces, using optical resonators and efficient nanophotonic collection strategies. Here, we present our efforts towards the development of photonic integrated circuits (PICs) for the entanglement of multiple NV quantum memories via photons. We describe NV-nanophotonic systems in the strong Purcell regime with optical cavity quality factors approaching 14,000 and electron spin coherence times exceeding 1.7 ms, a scalable method to create such spin–cavity systems via implantation of nitrogen and silicon ions, and how such devices can be used to shape the emission properties of spin defects to overcome their intrinsic optical inefficiencies, in particular of the nitrogen vacancy centre-an important step towards improved entanglement rates between distant qubits. Hybrid diamond–SiN on-chip networks are used for the integration of multiple functional NV-nanostructure systems and highly-efficient coupling to fiber architectures is demonstrated. For the generation of coherent optical photons, we exploit novel group-IV diamond defect centers that are quasi-deterministically coupled to optical nanocavities. Finally, we present how three quantum memories within _˜150 nmˆ3 can be simultaneously coherently controlled and read-out resonantly.

*Speaker

Hybrid Quantum Repeaters

Klaus Jöns * [1], Armando Rastelli [2], Rinaldo Trotta [3], Eden Figueroa [4], Val Zwiller [1]

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[2] JKU Linz – Australia
[3] Sapienza Rome – Italy
[4] Stony Brook University – United States

The realization of a quantum network, consisting of nodes and links, is currently pursued intensely with varying technologies to enable secure quantum communication. Photons are the only reliable quantum information carriers, and ideal candidates as flying qubits to link network nodes. Since classical amplification of quantum information to overcome transmission losses cannot be applied, quantum repeaters are needed along the communication channel. We are developing a hybrid quantum repeater architecture based on the Lloyd scheme [1] by interfacing solid state and atomic systems, to combine the strengths of both research fields. I will report on our efforts building a hybrid quantum repeater addressing the three main challenges: (i) Interfacing on-demand entangled photon pair sources with quantum memories, (ii) performing quantum teleportation operations and (iii) two-photon interference from remote quantum emitters.

Our hybrid approach interfaces single-photons emitted from semiconductor quantum dots with a hot rubidium vapor quantum memory, a first step for the realization of a quantum repeater protocol. We use two-photon resonantly excited strain-tunable quantum dots to generate frequency matched on-demand single-photons with unprecedented purity [2] and investigate their interaction with the rubidium atoms of the quantum memory [3]. In addition, we take advantage of these high quality semiconductor quantum dots to perform quantum teleportation using on-demand generated polarization entangled photon pairs [4] as well as two-photon interference-from two remote quantum dots [5]. I will discuss the advantages and challenges of this hybrid architecture, which forms a basic building block for the realization of quantum repeaters to overcome transmission losses in quantum communication applications.

References:
[1] S. Lloyd et al., Phys. Rev. Lett. **87**, 167903 (2001).
[2] L. Schweickert et al., Appl. Phys. Lett. **112**, 093106 (2018).
[3] L. Schweickert et al., arXiv: 1808.05921 (2018).
[4] M. Reindl et al. Science Advances **4**, 12, eaau1255 (2018).
[5] M. Reindl et al. Nano Lett. **17**(7), 4090-4095 (2017).

*Speaker

PASQuanS - Programmable Atomic Large-Scale Quantum Simulation

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[3] Max-Planck-Institut für Quantenoptik – Germany
[4] Institut d'Optique Graduate School – Institut d'Optique Graduate School – France

PASQuanS aims to perform a decisive transformative step for quantum simulation towards programmable analogue simulators addressing questions in fundamental science, materials development, quantum chemistry and real-world problems of high importance in industry. PASQuanS will build on the impressive achievements of quantum simulation platforms based on atoms and ions, scaling up these platforms and improving control methods to make these simulators fully programmable. We will push these already well-advanced platforms far beyond both the state-of-the-art and the reach of classical computation, and will demonstrate a quantum advantage for non-trivial problems, paving the way towards practical and industrial applications.
PASQuanS tightly unites five experimental groups with complementary methods to achieve the technological goals, connected with six theoretical teams focusing on certification, control techniques and applications of the programmable platforms, and five industrial partners in charge of the key developments of enabling technologies and possible commercial spin-offs of the project. We will also foster strong interactions with potential industrial end-users, identifying potential practical computing applications of our platforms relevant to a wide range of such end-users.
In this presentation, we will give an overview of our goals and an update on our initial progress.

*Speaker

Chapter 7

Thursday - 08:45-10:15 : Communication - 2 (Auditorium)

Building the UK Quantum Network

Joseph Pearse * [1], Adrian Wonfor [2], Catherine White [3], Arash Bahrami [1], Andrew Lord [3], Timothy Spiller [1]

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[2] The University of Cambridge – United Kingdom
[3] British Telecom – United Kingdom

Quantum Key Distribution (QKD) allows for information-theoretically secure communication using weak coherent pulses (single photons) and the properties of quantum mechanics. Any measurements made by a third party are detectable.
The need for such technology has become more apparent in recent years as advancements in quantum computing, as well as the discovery of vulnerabilities that could be exploited with only classical technology, have shown that our current encryption could be at risk.

A fundamental question in implementing QKD is integrating it with existing classical infrastructure. To do so allows it to be more widely implemented outside of research settings; a necessary goal if it is to compete with classical cryptography, irrespective of its potential for greater security.

In this talk, we discuss the UKQNTel project, comprising part of the UK Quantum Network. This project demonstrates effective integration by use of a resilient QKD protocol, pre-existing in-ground fibre for realistic losses, multiplexed classical and quantum channels, and sensible wavelength allocation to mitigate non-linear effects.

Part of the Quantum Communications Hub, UKQN is a QKD network in development in the UK. By its completion, QKD encrypted data may be sent between Ipswich and Bristol over 300 km.

A significant component of this project is a trusted node network running between BT optical research in Adastral Park, Ipswich, and the University of Cambridge, communicating securely over 120 km of standard, in-field optical fibre. This system uses four links each operating the Coherent One Way (COW) protocol and each generating between one and nine 256 bit AES keys per second. An end-to-end key is then distributed from Cambridge to Ipswich by XOR operation at each node and is used to encrypt 500 Gbps (5 x 100Gbps wavelengths) of data. This implementation demonstrates a new level of practicality for QKD, using "off the shelf" components to send high data rates with realistic equipment and restrictions.
In conclusion, we present design rules for more general multiplexed QKD networks. These include the constraints on classical channel powers when multiplexing with quantum channels, and how this can be resolved by designing a balanced power map; the use of optical filters; remote administration of the nodes; and secure key management.

*Speaker

Project CiViQ: Continuous Variable Quantum Communications

Valerio Pruneri * [1]

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The goal of the CiViQ project is to open a radically novel avenue towards flexible and cost-effective integration of quantum communication technologies, and in particular Continuous-Variable QKD, into emerging optical telecommunication networks.

CiViQ aims at a broad technological impact based on a systematic analysis of telecom-defined user-requirements. To this end CiViQ unites for the first time a broad interdisciplinary community of 21 partners with unique breadth of experience, involving major telecoms, integrators and developers of QKD. The work targets advancing both the QKD technology itself and the emerging "software network" approach to lay the foundations of future seamless integration of both. The technological advantage will more specifically aim to:

- Design architectures and implement protocol extensions of flexible "software based" networks for midterm country-wide QKD reach.
- Drive CV-QKD systems and components up to TRL 6, derive standardized set of interfaces, also allowing a network-aware software defined functionality and open modular development, and pursue cost reduction by seamless integration of off-the-shelf components.
- Push CV-QKD performance boundary forward by developing high-performance photonic integrated circuits (PIC) for CV-QKD, i.e. opening the way for ultra-low cost systems, and improve further the CV-QKD hallmark coexistence capability with standard WDM channels, i.e. reducing dramatically the barriers to optical network co-integration.
- Prepare actively for next-generation networks by developing core enabling technologies and protocols aiming at quantum communication over global distances with minimal trust assumptions.

CiViQ will culminate in a validation in true telecom network environment. Project-specific network integration and software development work will empower QKD to be used as a physical-layer-anchor securing critical infrastructures, with demonstration in QKD-extended software-defined networks.

*Speaker

A novel, simple source of quantum microwaves: Josephson-photonics devices

Björn Kubala * [1], Simon Dambach [1], Ciprian Padurariu [1], Joachim Ankerhold [1]

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In Josephson-photonics devices, Cooper pairs tunneling inelastically across a voltage-biased Josephson junction are exploited to generate non-classical microwave radiation. These simple devices are easily tunable to create a variety of diverse quantum states, and can thus be used to realize sources of single photons [1], pairs or higher-order bunches of photons, (two-mode) squeezed light [2], or other entangled quantum states.
At optical frequencies, a variety of non-classical states has found applications, particularly in quantum communication and sensing. In contrast, in the microwave domain efficient bright sources for non-classical states are missing so far and Josephson-photonics devices are promising to close this gap.

We will explain, how the inherent nonlinearity of the Josephson junction is directly responsible for the variety of different states and for their non-classical properties. By constructing high-impedance microwave cavities a regime can be reached, where the Josephson-system's equivalent of the fine-structure constant becomes of order one [1], so that strong-coupling quantum electrodynamics can be probed. This completely unexplored territory challenges our current theoretical understanding, but may also lead to new quantum-technology applications.

[1]C. Rolland, A. Peugeot, S. Dambach, M. Westig, B. Kubala, C. Altimiras, H. le Sueur, P. Joyez, D. Vion, P. Roche, D. Esteve, J. Ankerhold, F. Portier, *Antibunched photons emitted by a dc biased Josephson junction,* arxiv:1810.06217
[2]M. Westig, B. Kubala, O. Parlavecchio, Y. Mukharsky, C. Altimiras, P. Joyez, D. Vion, P. Roche, M. Hofheinz, D. Esteve, M. Trif, P. Simon, J. Ankerhold, and F. Portier, *Emission of Nonclassical Radiation by Inelastic Cooper Pair Tunneling,* Phys. Rev. Lett. **119**, 137001 (2017).

*Speaker

Project QRANGE: Quantum Random Number Generators: cheaper, faster and more secure

Hugo Zbinden [1]

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The generation of random numbers plays a crucial role in many applications in science and impacting society, in particular for simulation and cryptography. It is of fundamental importance that the generated numbers are truly random, as any deviation may adversely effect modelling or jeopardise security. Notably, recent breaches of cryptographic protocols have exploited weaknesses in the random number generation. In this context, schemes exploiting the inherent randomness of quantum physics have been extensively investigated. Quantum random number generation (QRNG) devices are now commercially available, which arguably represents one of the most successful developments of quantum technologies so far. QRANGE wants to push the QRNG technology further, allowing for a wide range of commercial applications of QRNG. We will build three different prototypes, which are cheaper, faster and more secure than existing devices: i) A fully integrated low-cost QRNG based on standard CMOS technology with a cost of the order of 1 for IoT. ii) A high-speed phase-diffusion scheme based on the interference of laser pulses with random phase relationship featuring bit rates of up to 10Gb/s. iii) Inspired by device independent schemes, a self-testing QRNG, which allows for a continuous estimation of the generated entropy, with few assumptions on the devices. Moreover, we will make considerable theoretical effort for modelling the devices, designing efficient randomness extractors and studying new semi device-independent concepts. Last but not least, we will work together with the competent institutions towards a full certification scheme of QRNG devices compliant with the highest security standards. This project addresses many key points in the call and is well-aligned with the vision and objectives of the Quantum Technologies Flagship, especially in terms of taking quantum technologies from the laboratory to industry with concrete prototype applications and marketable products.

Feasibility demonstration of Space Quantum Communications with MEO orbits for critical infrastructures

Luca Calderaro [1], Costantino Agnesi [2], Daniele Dequal [3], Francesco Vedovato [1], Matteo Schiavon [1], Alberto Santamato [2], Vincenza Luceri [4], Giuseppe Bianco [5], Giuseppe Vallone [1,6], Paolo Villoresi * [1,6]

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The paradigm shift that Quantum Communications represent vs. classical counterpart allows envisaging the global application of Quantum Information protocols as the cryptographic key distribution as well as of the use of the qubits as a probe for fundamental tests on a scale beyond terrestrial limits.
Critical infrastructures as the Global Positioning Satellite Systems have operations are crucially dependent on secure transmission: from ground stations on Earth, different types of data are exchanged with satellites at about 19000 km of altitude.

Due to optical losses, most of the demonstrations of satellite QCs were limited, so far, to LEO satellites. However, the high orbital velocity of LEO satellites limits their visibility periods from the ground station, and subsequently the time available for QCs to just few minutes per passage. Conversely, the use of satellites at higher orbits can greatly extend the communication time, reaching few hours in the case of GNSS. Furthermore, QCs could offer interesting solutions for GNSS security for both satellite-to-ground and inter-satellite links, offering novel and unconditionally secure protocols for the authentication, integrity and confidentiality of exchanged signals.

We experimentally demonstrate the feasibility of QC between a GNSS satellite and a ground station, over a channel length of about 20000 km by using current technology: the first exchange of few photons per pulse between two different satellites of GLONASS constellation and the Space Geodesy Centre of the Italian Space Agency in Matera (Italy) is demonstrated by exploiting the passive retro-reflectors mounted on the satellites. By estimating the actual losses of such a channel, we can evaluate the characteristics of both a dedicated quantum payload and a receiving ground station, hence attesting the feasibility of QC from GNSS in terms of achievable signal- to-noise ratio and detection rate.

Moreover, the perspective of the extension to QC in Europe from the LEO types of orbit to MEO ones, like the GNSS discussed here and the GEO, as well as the scenario of a network for secure communications relying on satellites as a complementary asset to the fibers on ground will be described. The vision of such Space QComm infrastructure is to improve the security in Europe.

*Speaker

Supporting the commercialisation of quantum key distribution technology with SI-traceable measurements

Robert Kirkwood * [1], Anthony Vaquero-Stainer [1,2], Christopher Chunnilall [1], Alastair Sinclair [1]

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Quantum key distribution (QKD) is arguably one of the most commercially advanced quantum technologies with a growing number of industrial providers. It uses communication at the single-photon level to create a shared secret encryption key between two distant parties. The assessment of key security requires a theoretical model of the system as well as accurate knowledge of the quantum hardware's physical operating characteristics at the time of key creation.
The National Physical Laboratory (NPL) has developed test instrumentation to characterise this new technology which can be synchronised to GHz-clocked QKD hardware to perform SI-traceable optical measurements at the single-photon level. NPL has also recently participated in comparisons with other national metrology institutes to verify the accuracy of its single-photon measurements.

The creation of industrial standards is important to create an assurance framework for these products which will increase end user confidence and accelerate commercialisation. NPL has used its expertise in QKD metrology to lead the drafting of the first ETSI specification to document protocols for characterising QKD components.
We present our work towards physical security verification of QKD components and modules, and introduce our efforts to extend this to chip-scale integrated QKD devices.

*Speaker

Chapter 8

Thursday - 08:45-10:15 : Sensing - 1 (upper room)

Quantum jump metrology

Almut Beige * [1], Lewis Clark [2], Adam Stokes [3]

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[3] University of Manchester – United Kingdom

Quantum metrology exploits quantum correlations in specially prepared entangled or other non-classical states to perform measurements that exceed the standard quantum limit. Typically though, such states are hard to engineer, particularly when larger numbers of resources are desired. As an alternative, this paper aims to establish quantum jump metrology which is based on generalised sequential measurements as a general design principle for quantum metrology and discusses how to exploit open quantum systems to obtain a quantum enhancement. By analysing a simple toy model, we illustrate that parameter-dependent quantum feedback can indeed be used to exceed the standard quantum limit without the need for complex state preparation [1,2].

[1]L. A. Clark, A. Stokes and A. Beige, *Quantum-enhanced metrology with the single-mode coherent states of an optical cavity inside a quantum feedback loop,* Phys. Rev. A **94**, 023840 (2016).
[2]L. A. Clark, A. Stokes and A. Beige, *Quantum jump metrology*, submitted (2019); arXiv:1811.01004.

*Speaker

UK National Quantum Technology Hub in Sensors and Metrology

Yeshpal Singh * [1]

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I will present the activites of the UK National Quantum Technology Hub in Sensors and Metrology. There will be a particular focus on the potential commerical applications and impact of quantum sensors for the economy, having a potential to change the knowledge economy and impact on10% of GDP.

*Speaker

Quantum sensors with matter waves : geodesy, navigation and general relativity

Philippe Bouyer * [1]

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The remarkable success of atom coherent manipulation techniques has motivated competitive research and development in precision metrology. Matter-wave inertial sensors – accelerometers, gyrometers, gravimeters – based on these techniques are all at the forefront of their respective measurement classes. Atom inertial sensors provide nowadays about the best accelerometers and gravimeters and allow, for instance, to make the most precise monitoring of gravity or to device precise tests of the weak equivalence principle (WEP). I present here some recent advances in theses fields:
The outstanding developments of laser-cooling techniques and related technologies allowed the demonstration of an airborne matter-wave interferometers, which operated in the micro-gravity environment created during the parabolic flights of the Novespace Zero-g aircraft. Using two atomic species (for instance 39K and 87Rb) allows to verify that two massive bodies will undergo the same gravitational acceleration regardless of their mass or composition, allowing a test of the Weak Equivalence Principle (WEP).

New concepts of matter-wave interferometry can be used to study sub Hertz variations of the strain tensor of space-time and gravitation. For instance, the MIGA instrument which is currently built in France, will allow the monitoring of the evolution of the gravitational field at unprecedented sensitivity, which will be exploited both for geophysical studies and for Gravitational Waves (GWs) detection.

The starting point for many experiments aimed at studying fundamental physics is to prepare a pure sample in terms of its energy, spin and momentum before injecting into an atom interferometer, spectrometer or quantum simulator. I will present an all-optical technique to prepare ultra-cold sample in magnetically insensitive state with high purity, a versatile preparation scheme particularly well suited to performing matter-wave interferometry with species exhibiting closely separated hyperfine levels, such as the isotopes of lithium and potassium.
I will finally discuss how precision atom interferometry can be used to perform long-term, drift-free integration even in the harsh environment of the plane, and thus provide a new tool for precision measurement and navigation.

*Speaker

Relaxation and Dephasing in Hot Electron Quantum Optics Interferometry

Lewis Clark * [1], Clarissa Barratt [1], Masaya Kataoka [2], Nathan Johnson [3], Clive Emary [1]

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Single electron sources, and in particular those based on dynamic quantum dots [1], are being developed to provide the missing leg of the so-called quantum metrology triangle, the current standard. When combined with energy and time-resolved detection [2], electrons from these sources provide us with a new platform to probe fundamental semiconductor physics in unprecedented detail, and with which to develop quantum-technology applications.

In this talk, we discuss coupling single-electron sources into interferometer geometries, such as the Mach-Zehnder interferometer, where the visibility of the quantum interference acts as a sensitive probe of the properties both of the emitted electrons and their environment. We focus on the relaxation and loss of coherence of single electrons emitted from dynamical quantum dots. These sources inject "hot" electrons with energy significantly in excess of the Fermi energy. In a strong magnetic field, this new energy regime suppresses Coulomb effects, which are dominant at low energies, but also opens new relaxation channels, most importantly phonon emission [3,4].

We show how experiments can be used to extract various inelastic rates. Moreover, we derive strategies for minimising the effects of these inelastic processes, thus maximising the quantum-coherent properties of the electrons [5].

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*Speaker

Single microwave photon detection by an underdamped Josephson junction

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Devices based on superconducting technologies have demonstrated their competitiveness and partly their supremacy compared to real quantum systems in the realization of modern quantum technologies. They exploit the Josephson junction's nonlinearity to create objects with controllable quantized level structures and their interaction and coupling can be controlled by circuit design. On the other hand, the frequency range at which these devices are operational is limited to the microwave range by their superconducting properties. Therefore, appropriate control and measurement devices, that are well-established in quantum optics, need to be developed. One such example is the microwave single photon detector.
In our approach, we consider the photon induced switching of an underdamped Josephson junction from its zero to the finite-voltage state as possible detection mechanism. In a first experimental investigation, the microwave field is stored inside of a coplanar waveguide resonator. In this configuration, the current amplitude corresponding to a single photon can be significantly larger than the switching current distribution width of an appropriate Josephson junction [1].

We experimentally tested the influence of several control parameters, as for example the temperature and microwave power, to the switching current distributions of the coupled system [2]. This characterization of a prototype device achieved a sensitivity of about 0.5 on the single photon input power level of a classical tone. Additionally, our experiments demonstrate a rich dynamic connected to the nonlinearity of the Josephson junction [3]many of which are predicted by theoretical analysis [4]. The nonlinearity strongly influences to the detection performance and our investigations promise sensitivities close to 1 for an optimized device.

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*Speaker

Microwave field imaging with atomic vapor cells

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Microwave devices and circuits are the cornerstones of modern communication technology and precision instrumentation, with applications ranging from wireless networks, satellite communication, navigation, radar systems to precision measurement. In order to develop and test microwave devices, a calibrated technique for high-resolution non-perturbative imaging of microwave fields is needed. Microwave detectors with high spatial resolution and low crosstalk are also essential for emerging applications of microwaves in medical imaging [1].

Our group developed a calibration-free technique for high-resolution imaging of microwave fields using atoms in miniaturized vapor cells as sensors [2]. In this technique, the microwave field to be measured drives Rabi oscillations on atomic hyperfine transitions. The oscillations are recorded in a spatially resolved way by absorption imaging with a laser and a camera. From the measured distribution of Rabi frequencies we obtain an image of the microwave field distribution. All vector components of the microwave magnetic field can be imaged and the technique is intrinsically calibrated because the properties of the atomic transitions are precisely known. Using a custom vapor cell with thin walls our technique provides a spatial resolution of < 100 μm [3].

By applying a static magnetic field (up to Tesla level), the Zeeman splitting can be made larger than the hyperfine splitting (hyperfine Paschen-Back regime) and microwave magnetic fields with frequencies ranging from a few GHz to a few tens of GHz can be detected [4]. The experimental apparatus is simple and compact and does not require cryogenics or ultra-high vacuum, making the technique attractive for applications outside the laboratory. We will present our activities on frequency-tunable microwave field imaging in the framework of the quantum flagship project MACQSIMAL.

*Speaker

Chapter 9

Thursday - 08:45-10:15 : Simulation - 2 (Platine)

Analogue randomized benchmarking for testing quantum simulation

Ellen Derbyshire * [1], Jorge Yago Malo [2], Petros Wallden [1], Andrew Daley [2], Elham Kashefi [1]

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[2] University of Strathclyde – United Kingdom

Quantum simulation is a promising area that could offer insight into and applications of quantum systems that are not necessarily suitable for universal quantum computation, as well as practical calculations on a timescale shorter than universal quantum computation. In analogue quantum simulation engineered quantum devices evolve continuously through time, replicating the behaviour of other quantum phenomena. These could potentially be applied to solve problems from quantum chemistry to materials science, machine learning and optimisation. An important limitation in the absence of error correction is how to verify or certify results that go beyond existing classical computation. With long-range Hamiltonians and larger system sizes, the final state of the quantum evolution is currently classically intractable up to 10s of qubits, for most analogue quantum simulators. We aim to lift this limitation, and to develop tools that can be used to test the correctness of analogue quantum simulators. In particular, we built on the more developed existing techniques for digital quantum simulation and universal quantum computing, and extend the randomized benchmarking (RB) method for use in the analogue setting. This technique quantifies the average strength of errors when running a long random circuit, incorporating the errors from state preparation and measurement. Currently techniques such as quantum state or process tomography are not scalable and do not incorporate state preparation and measurement errors. To apply RB to analogue quantum simulators, we give a general protocol relying on generating an approximate unitary t-design with time evolution operators natural for the chosen analogue quantum simulator, by perturbing the Hamiltonian by a small amount for each time-step. As a first step, we consider a specific example of a 1D spin chain of trapped ions and perturb the Hamiltonian with an extra disorder term. Our preliminary results do not perfectly match the theoretical conjectured behaviour, but by refining the method (of generating approximate unitary t-designs) and further developing the theory behind the decay model used for RB, we anticipate that this will lead to a more efficient and scalable technique for testing the reliability of analogue quantum simulators.

*Speaker

The QOMBS project: first results and challenges

Francesco Minardi * [1]

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We will discuss preliminary results and challenges of the QOMBS project. The Qombs project aims to create a quantum simulator platform made of ultracold atoms in optical lattices. The quantum platform will allow to design and engineer a new generation of quantum cascade laser frequency combs. This unprecedented quantum simulation of semiconductor structures will endow the devices with brand new features, like non-classical emission modes, entanglement among the modes of the comb and parametric generation of comb patterns far from the central emission frequency. In parallel, the quantum simulation will allow to improve present-day performances of quantum cascade lasers (QCLs) and quantum well structures for photon detection. Full quantum simulation will be followed by real manufacturing and state-of-the-art characterization.

*Speaker

Experimental studies of spin dynamics in an atomic dipolar condensate

Olivier Gorceix * [1], Steven Lepoutre [2], Lucas Gabardos [3], Kaci Kechadi [2], Paolo Pedri [2], Bruno Naylor [3], Etienne Maréchal [2], Laurent Vernac [2], Bruno Laburthe-Tolra [2]

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We report on quantum simulation experiments performed using a chromium BEC loaded into deep 3D optical lattices with important improvements relative to previous works [1,2]. The out-of-equilibrium dynamics of the Cr multicomponent spin-3 condensate is monitored and the outcomes are compared to theoretical models developed in A M Rey's group. Our system emulate the XXZ Heisenberg model with inter-site dipolar magnetic couplings; by properly choosing the experimental parameters and procedures, we are able to study quantum thermalization and entanglement dynamics issues [3]. In a complementary set of experiments, we demonstrate a new type of magnon-like collective excitation triggered by a magnetic gradient acting on a bulk Cr BEC. This new type of collective excitation in a ferromagnetic quantum gas was not reported previously [4].
We thank A.-M. Rey (NIST, Boulder, USA), J. Schachenmayer (CNRS, Strasbourg, France) et B. Zhu (ITAMP, Harvard, USA) for their highly valuable contributions to the interpretation of the results in {3]. This work is supported by the French Ministry for Research MESR within CPER contracts, by Université Sorbonne Paris Cité, by DIM Nano-K / IFRAF of Région Ile-de-France and by CEFIPRA (contracts LORIC5404-1 et PPKC).

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*Speaker

Simulating Nagaoka Ferromagnetism in a 2×2 Quantum Dot Array

Uditendu Mukhopadhyay * [1], Juan Pablo Dehollain [1], Vincent P. Michal [1], Christian Reichl [2], Werner Wegscheider [2], Bernhard Wunsch [3], Mark Rudner [4], Eugene Demler [3], Lieven Vandersypen [1]

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[4] Center for Quantum Devices, University of Copenhagen – Denmark

The Fermi-Hubbard model provides a description of interacting electrons in a lattice. The interaction between electrons in arrays of electrostatically defined quantum dots is naturally described by a Fermi-Hubbard Hamiltonian; moreover, the high-degree of tunability in these systems make them a perfect platform to explore different regimes of the Hubbard model through analogue quantum simulations[1].
Last year we established a 2x2 gate-defined quantum dot array as a promising solid-state analogue quantum simulator[2]. Here we present results on simulation of Nagaoka Ferromagnetism, which predicts a ferromagnetic ground state in an almost-half-filled lattice[3,4]. Evidence for this ground state is observed with 3 electrons in the 2x2 dot array. We use the high-levels of control in our system to manipulate the Hamiltonian parameters and perform measurements that test the validity of our interpretation. For example, breaking the periodic boundary condition of the plaquette destroys the signature of the ferromagnetic state. Moreover, the signature can also be broken when a small magnetic field is applied perpendicular to the plane of the dot-array. However, this ground state shows striking robustness to offset in local energy of any dot. To our knowledge, this is the first experimental verification of Nagaoka's prediction as well as the first simulation of magnetism using quantum dot arrays.

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*Speaker

Controlling symmetry and localization with artificial gauge fields in disordered quantum systems

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Anderson Localization is the absence of diffusion in certain disordered media. The transport and localization properties of disordered quantum systems are greatly affected by symmetries. Here, we present a novel technique [1]which allows the realization an artificial gauge field in a synthetic (temporal) dimension of a disordered, periodically driven (Floquet) quantum system. Our technique is used experimentally to control the Time-Reversal Symmetry properties of the Phase-Shifted Quantum Kicked Rotor – a quasi-1D disordered system in momentum space.
Using this system, we were recently able to provide the first observation and characterization of a direct 'microscopic' interference smoking gun of the Anderson Localization, the so-called "Coherent Forward Scattering" (CFS) phenomenon – thus confirming its very recent theoretical prediction. This result is complemented by an accurate measurement of the universal scaling function β(g) in two different universality classes. The Coherent Forward Scattering, in conjunction with its weak-localization counterpart, the "Coherent Backscattering" (CBS) [2], can be extremely valuable tools for future probing novel phenomena, emerging from the interplay of many-body effects or symmetry properties with the Anderson physics.

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*Speaker

Chapter 10

Thursday - 10:45-12:15 : BSCC - 3 (Auditorium)

Temporal mode selective measurement and purification of quantum light

Vahid Ansari * [1], John M Donohue [1], Markus Allgaier [1], Linda Sansoni [1], Benjamin Brecht [1], Jonathan Roslund [2], Nicolas Treps [2], Georg Harder [1], Christine Silberhorn [1]

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Single photons in clearly distinguishable, accurately controllable, and practically measurable modes are essential for photonic implementations of quantum information protocols. The time-frequency photonic degree of freedom offers an attractive framework for quantum communication and quantum information processing. Unlike polarisation and spatial encodings, information encoded in the time-frequency domain is robust through fibre-optic and waveguide transmission, making it a natural candidate for both long-distance quantum communication and compact integrated devices. The time-frequency basis also allows for expanded per-photon information rates and enables large-scale networking through high-dimensional encoding, multiplexing, and entanglement. Here we present a complete set of tools to control the temporal-mode structure of quantum light sources and perform mode-selective quantum operations and measurements. As a source of quantum light, we use heralded single photons from an engineered parametric down-conversion PDC source where we orchestrate the modal structure of the photon pair by spectral modulation of the pump field. This provides a versatile source of entangled temporal-modes, capable of generating maximally entangled states with a controllable number of modes. Then we use an engineered sum-frequency generation process, dubbed the quantum pulse gate (QPG), to perform quantum operations on arbitrary temporal modes. Regardless of the temporal mode structure of the PDC photons, we show that the QPG can select a single temporal mode from an ensemble, demonstrating its usefulness as a temporal-mode projective measurement and as a purifier. We use a QPG to tomographically reconstruct the seven-dimensional temporal-mode density matrix of heralded single photons, showing that QPG measurements are sensitive to time-frequency structure of light beyond intensity-only measurements. The high signal-to-noise ratios and high mode-selectivity of these operations, positions the QPG as a temporal-mode analyser for communication networks or as an add-drop component to build general unitaries and quantum logic gates.

*Speaker

Electric-field control of CMOS silicon spin qubits

Yann-Michel Niquet * [1], Andrea Corna [2], Alessandro Crippa [2], Romain Maurand [2], Léo Bourdet [1], Benjamin Venitucci [1], Jing Li [1], Heorhii Bohuslavsky [2], Anthony Amisse [2], Dharmraj Kotekar-Patil [2], Romain Laviéveille [3], Sylvain Barraud [3], Xavier Jehl [2], Louis Hutin [3], Marc Sanquer [2], Maud Vinet [3], Silvano De Franceschi [2]

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Silicon is a promising material for solid-state quantum computation based on spin quantum bits (qubits). Since 2012, various quantum bits have been implemented in Si/SiGe and Si/SiO2 structures, with the demonstration of high fidelity single and two qubit gates. More recently, we have reported a spin qubit device implemented on a foundry-compatible Si CMOS platform [1]. The device, fabricated using a silicon-on-insulator (SOI) nanowire MOSFET technology, is in essence a two-gate field effect transistor. Here we will review our latest results on this specific structure. More precisely, we will show that the electrical control of the spin dynamics is possible for both electrons [2]and holes [3]. In hole spin qubits we demonstrate fast coherent control with Rabi frequencies as large as 80 MHz and an inhomogeneous dephasing time close to 300 ns. Tight-binding and k.p simulations support these results, and unveil the role and fingerprints of spin-orbit coupling in the conduction and valence bands of silicon. Hole spin qubits show, notably, a very rich physics related to the interplay between electric and magnetic fields. We will discuss, in particular, the role of symmetries in such semiconductor qubits, and how the wave functions, Rabi frequency and coherence times can in principle be tuned by the interplay between structural confinement in the nanowire and electrical confinement by the front and back gates [5]. Modeling also open paths towards more efficient electrical spin manipulation [4]. By demonstrating spin qubit functionality in conventional transistor-like layout and process flow, our results bear relevance for a future up-scaling of silicon qubit architectures.

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*Speaker

Superconducting Josephson junctions in Si and Ge based scalable technology.

Florian Vigneau [1], Francesca Chiodi [2], Sergey Frolov [3], Romain Maurand [1], Raisei Mizokuchi [1], Amir Sammak [4,5], Giordano Scappucci [4], Marco Tagliaferri [1], Tom Vethaak [1], Silvano De Franceschi [1], François Lefloch * [1]

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Quantum technology based on superconducting qubits is by far the most advanced technology for quantum information. The key quantum element consists of a metallic tunnel Josephson junctions embedded in a superconducting environment (transmon). Such implementation has been very successful and has led to complex geometries for quantum computing. However, the road is long towards a true quantum computer for which some thousands of qubits or more will have to work together. That is why a scalable technology for implementation of qubits is already necessary. The silicon and germanium technology clearly has the advantage of scalability but its use for quantum technology is still at his early stage with the recent demonstration of a silicon CMOS spin qubit [1].
An alternative to the usual aluminum based metallic technology for superconducting qubits has been recently demonstrated with the realization of a gate tunable transmon (gatemon) using hybrid superconducting / semiconducting (S/Sm) nanostructures [2]. Such a result opens new perspectives for the use of the semiconducting technology for superconducting quantum applications.

In this contribution, I propose to present the latest developments on hybrid S/Sm nanostructures that are fully compatible with the CMOS technology. Those include the demonstration of Ge based tunable Josephson effect [3]and the realization of all silicon Josephson junctions [4]using pulsed laser annealing.

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*Speaker

Cooper pair splitting, thermoelectricity, and quantum heat engine in graphene NSN system

Zhenbing Tan [1], Nikita Kirsanov [2], Antti Laitinen [1], Dmitry Golubev [1], Gordey Lesovik [1,2], Pertti Hakonen * [1]

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[2] Moscow Institute of Physics and Technology – Russia

Split Cooper pairs (CPS) form a natural source of entangled electrons, which provides a basic ingredient for quantum information [1, 2]. We have theoretically investigated thermal and electrical effects emerging from Cooper pair splitting (CPS) and elastic co-tunneling (EC) in hybrid normal-superconducting-normal (NSN) structures, in particular, using a setting with graphene as the normal conductor. Our analysis [3]indicates that a finite superconductor can, in principle, mediate heat flow between normal leads, and that NSN devices can be applied to heat transport control and cooling of microstructures. The heat flow control is based on the interplay of CPS and EC processes which leads to seemingly contradictory behavior with the Second law of thermodynamics. We have also analyzed the setting as a new quantum heat engine and discuss its advantages compared with other nanoscale heat engines.
Furthermore, we present first results on non-local thermoelectricity in a CPS device based on 2D materials. In our NSN device made of graphene, switching supercurrents are employed to determine the thermal gradient imposed on the sample by a patterned graphene heater. In our design, two well-shielded quantum dots are only connected through the superconducting lead, which facilitates tuning of the bias and gate on each quantum dot separately without influencing the resonance level directly. Consequently, we are able to probe changes in Cooper pair splitting as well as non-local thermopower while sweeping separately the energy levels in the quantum dots. The observed thermopower results can be assigned to a competition of CPS and EC processes driven by thermal gradient [3-5].

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*Speaker

Quantum metamaterials composed of superconducting flux qubits

Evgeni Il'ichev * [1]

[1] leibniz institute of photonic technology – Germany

A superconducting quantum metamaterials, realized as an array of different type of flux qubits, have been fabricated and tested. Collective mode of its operation was experimentally demonstrated. For metamaterial based on double-loop flux qubits, the transmission periodically depends on the applied magnetic field. Field-controlled switching between two ground state configurations of the meta-atoms induces a suppression of the transmission. Additionally, their excitation leads to resonant enhancement of the transmission.

*Speaker

Technology and Engineering for Quantum Technologies

Iuliana Radu * [1], Bogdan Govoreanu [1], Anton Potocnik [1], Massimo Mongillo [1], Fahd Mohiyaddin [1], Dan Mocuta [1], Anda Mocuta [1], James Lee [1], Stefan Kubicek [1], Danny Wan [1], Bt Chan [1], Laurent Souriau [1], Bertrand Parvais [1]

[1] IMEC – Belgium

In this presentation we will outline imec's activities on quantum computing and engineering for quantum computing. We will describe how to bring quantum computing devices to readiness for technological adoption and how we are developing the 300mm fab infrastructure framework for hardware for quantum technologies.
Three types of qubits are potentially compatible with standard CMOS fab fabrication. We will discuss our assessment for each of these concepts and highlight the missing scientific components for these concepts. Imec is bringing up platforms for qubit device fabrication for each of these qubits. On overview of the progress will be given here. We will discuss the changes that need to be implemented in standard CMOS processing to fabricate these devices. Differences between usual lab fabrication and standard fab processing might limit or might enhance qubit performance. This talk will outline some of these differences and steps that we are taking to improve device performance, trying to separate fact from folklore.
The promise of using a 300mm fab for building qubit devices comes not only from higher precision for qubit fabrication and reduced device variability, but also from the possibility to integrate qubit arrays with classical circuitry to drive them. As expected, CMOS device changes when operated at low temperature. We will describe here some of these changes and the potential implications from a circuit viewpoint.

*Speaker

Chapter 11

Thursday - 10:45-12:15 : Communication 3 (upper room)

Security and implementation of practical unforgeable quantum money

Mathieu Bozzio * [1], Adeline Orieux [2], Luis Trigo Vidarte [3], Frédéric Grosshans [4], Isabelle Zaquine [3], Iordanis Kerenidis [5], Eleni Diamanti *

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Wiesner's unforgeable quantum money scheme is widely celebrated as the first quantum information application. The principle is to ensure unforgeability of tokens, banknotes or credit cards by encoding them with qubit states prepared in one of two possible conjugate bases. The no-cloning theorem then ensures that a malicious party willing to duplicate the money cannot copy the unknown qubit state perfectly. Despite quantum money's central role in quantum cryptography, its experimental implementation has remained elusive because of the lack of realistic protocols adapted to practical quantum storage devices and verification techniques. Our contribution is two-fold. First, we experimentally demonstrate a quantum credit card scheme that rigorously satisfies the security condition for unforgeability for a dishonest client and a trusted payment terminal. We use a practical system exploiting single-photon polarization encoding of highly attenuated coherent states of light for on-the-fly credit card state generation and readout. Second, we derive a practical semi device-independent security proof which allows the future implementation of a quantum money scheme with an untrusted payment terminal. Both the trusted terminal implementation and the untrusted terminal security proof include classical verification, and are designed to be compatible with state-of-the-art quantum memories (both single-emitter type and atomic ensemble type), which have been taken into account in the security analysis, together with all system imperfections (npj Quantum Information, 4, 5, (2018) + ArXiv to appear soon).

*Speaker

Classical delegation of secret qubits and Applications in quantum protocols

Alexandru Cojocaru * [1], Leo Colisson [2], Elham Kashefi [1,2], Petros Wallden [1]

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We define the functionality of delegated pseudo-secret random qubit generator (PSRQG), where a classical client can instruct the preparation of a sequence of random qubits at some distant party. Their classical description is (computationally) unknown to any other party (including the distant party preparing them) but known to the client. We emphasize the unique feature that no quantum communication is required to implement PSRQG. This enables classical clients to perform a class of quantum communication protocols with only a public classical channel between the classical clients and a quantum server. A key such example is the delegated universal blind quantum computing, for example using our functionality one could achieve
a purely classical-client computational secure verifiable delegated universal quantum computing (also referred to as verifiable blind quantum computation). We give a concrete protocol (QFactory) implementing PSRQG, using the Learning-With-Errors problem to construct a trapdoor one-way function with certain desired properties (quantum-safe, two-regular, collision-resistant). We then prove the security in the Quantum-Honest-But-Curious setting and briefly discuss the extension to the malicious case and explain further interesting applications of this functionality, such as: classical-client quantum fully homomorphic encryption and quantum multiparty computation.
Further details can be found in the full paper:
https://arxiv.org/abs/1802.08759

*Speaker

Quantum random number generation with partially characterised devices based on bounded energy

Davide Rusca * [1], Thomas Van Himbeeck [2,3], Anthony Martin [1], Jonatan Brask [4], Weixu Shi [5], Stefano Pironio [2], Nicolas Brunner [1], Hugo Zbinden [1]

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Random numbers are central to cryptography, stochastic simulations, random sampling, and gaming. In particular, communication security relies critically on high-quality, private randomness. For such applications, a good source of randomness must produce an output with a high entropy that can be certified relative to any potential untrusted parties, and to be practical it should do so at a high rate.
Here, we demonstrate semi-device independent QRNG based on a natural, physical assumption, namely a bound on the average energy transmitted between the preparation and measurement devices. This assumption is straightforward to verify experimentally which ensures a high level of security.

We consider a prepare-and-measure scenario, with a binary input x for the preparation device, and a binary output b for the measurement device. For each input, the preparation device emits a quantum state, which is sent to the measurement device. Thus, b may depend on x, but only via the transmitted quantum states. In addition, there may be internal classical noise affecting both the state preparation and the measurements. We allow this classical noise to be correlated between the devices, i.e. they have shared randomness. The certification will be based on the observed correlations, and an assumption about the energy available to encode the quantum states. Apart from this assumption, the devices are treated as black boxes.

The experimental implementation consists in modulating the amplitude of a signal coherent state (produced by a laser). The transmitted state is then measured by interfering it with a local oscillator on a balanced beam splitter, followed by single-photon threshold detection in one output port. In the event the detector does not click, we assign the output b = 0, while b = 1 corresponds to a click. The average transmitted energy is given by the mean photon number and can be easily measured by a standard power-meter. The local oscillator carries no information about x and is not considered to be part of the prepared state.
We compute (via semidefinite programming) the amount of true quantum randomness extractable from the raw data obtaining a certifiable entropy of H = 0:14 per round, which, at a system rate of 12.5 MHz, results in a maximum output random bit rate of 1.75 MHz.

*Speaker

Anonymity for practical quantum networks

Anupama Unnikrishnan * [1], Ian Macfarlane [2], Richard Yi [3], Eleni Diamanti [4], Damian Markham [4], Iordanis Kerenidis [5]

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Quantum communication networks have the potential to revolutionise information and communication technologies. A crucial yet challenging functionality required in any network is the ability to guarantee the anonymity of two parties, the Sender and the Receiver, when they wish to transmit a message through the network. Such anonymity is an increasingly valuable commodity in our information age. Here, we present a new protocol for players in a network to communicate both classical and quantum messages in a way that protects identity. Our work combines the power of classical and quantum protocols in a novel way, guaranteeing security against untrusted sources. As required for a realistic network, we ensure anonymity even in the presence of malicious parties. We define error-tolerant notions of anonymity, essential for realistic implementations, which we show can be achieved. Furthermore, this work highlights a particularly unclassical nature of quantum networks: as far as we know, such anonymity (for classical messages) is not possible classically without the extra (and difficult) resource of simultaneous broadcasting. Crucially, compared to previous results, we demonstrate a dramatic reduction in the required resources, leading to a practical protocol that can be performed with currently available experimental technology. (arXiv:1811.04729)

*Speaker

Heralded entanglement in quantum communication networks

Rob Thew * [1]

[1] University of Geneva – Switzerland

We've been developing a scheme for heralded single-photon path entanglement and a displacement-based measurement scheme to study quantum networks. The measurement scheme is a hybrid approach which uses single photon counting detectors and weak, less than one photon, coherent states in an optical displacement with some analogies with homodyne detection. We briefly present some recent results in the direction of device-independent and multipartite certification. We address some of the advantages in terms of scaling for these systems and their connection to quantum repeater architectures.
We present results using several different schemes, including heralded photon amplification, a teleportation-based protocol, as well as entanglement swapping to overcome loss in heralding entanglement in communication networks. The challenge here is to overcome this loss, so as to consider device independent protocols and the associated constraints on system efficiency over long distances. To this end, we have also demonstrated detection loophole free EPR steering, a semi-device independent protocol for certifying entanglement.
We previously developed and demonstrated an entanglement witness for multipartite entanglement, with results for a tripartite scenario. Based on previous work for genuine multi-partite entanglement, we look at the challenges of pushing this to larger network configurations, both experimentally as well as developing new approaches to simplify the experimental demands in certifying large entangled networks.

*Speaker

NanoBob: Quantum Secure Communication with a CubeSat

Erik Kerstel * [1,2], Arnaud Gardelein [3], Mathieu Barthélémy [4], Benoît Boulanger [5], The Csug Team [6], Sébastien Tanzilli [7], Matthias Fink [8], Siddarth Joshi [9], Rupert Ursin [10]

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Quantum Key Distribution, the quantum secure exchange of secret keys between two parties, provides a level of communication security that cannot be obtained by classical cryptographic means. Quantum information can be coded into polarization states of single photons and the experiment designed such that eavesdropping on the exchange would necessarily lead to detectable errors. The intrinsic security largely outweighs the disadvantages of additional complexity and cost, at least in the case of certain critical infrastructures. QKD has already proven its practicality in fiber network implementations, for which commercial solutions are available. However, losses limit the distance between two parties to a few hundreds of km, as the no-cloning theorem prohibits the use of simple optical amplifiers, whereas quantum repeaters remain an extremely challenging solution. For the foreseeable future, satellites are the only option enabling exchanging secret keys on a global scale, while limiting the number of trusted relay nodes in the network. NanoBob will demonstrate QKD between an optical ground station (OGS) and a nanosatellite. Keeping the entangled photon source on the ground, the space segment becomes less complex, yielding a lower power consumption, smaller package, and increased reliability; all at a lower cost, especially when multiple satellites service a limited number of OGSs. The lower link efficiency of the uplink configuration can be countered by implementing adaptive optics in the OGS. The space segment payload is also versatile: the receiver is compatible with multiple QKD protocols and other quantum physics experiments. In order to extend the geographical reach of the OGSs at the metropolitan scale and the number of end-users that can exploit the same OGS we will design a "plug-and-play" synchronized quantum network, thus demonstrating a complete infrastructure for global and metropolitan scale QKD.

We discuss the mission concept and the outcome of the definition and feasibility studies carried out so far. To our knowledge, NanoBob, having completed its Mission Definition Review follow-

*Speaker

ing CNES/ESA guidelines, is so far the most advanced European project focusing on the use of entangled photons and a CubeSat platform [1].

[1]Kerstel E. *et al.* Eur. Phys. J. – QT. 2018; http://rdcu.be/1uEO

Chapter 12

Thursday - 10:45-12:15 : Sensing - 2 (Platine)

Spin squeezing in a trapped atom clock and waveguide design for on chip atom interferometry

Théo Laudat [1], Mengzi Huang [2], Tommaso Mazzoni [1], Alice Sinatra [2], Peter Rosenbusch [1], Jakob Reichel [2], William Dubosclard [1], Jean-Marc Martin [1], Carlos L. Garrido Alzar * [1]

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The observation of spontaneous spin squeezing in a standard Ramsey sequence applied to a two-component Bose–Einstein condensate (BEC) of 87Rb atoms is presented. The atoms are trapped in the elongated magnetic trap of an atom chip, and the squeezing is generated by state-dependent collisional interactions, despite the near-identical scattering lengths of the spin states. In this proof-of-principle experiment, we observe a metrological spin squeezing that reaches 1.3±0.4 dB for 5000 atoms, with a contrast of 90±1%. This method may be applied to realize spin-squeezed BEC sources for atom interferometry without the need for cavities, state-dependent potentials or Feshbach resonances. An attractive approach would be to use the naturally occurring spatial separation as a nonlinear beam splitter for a matter wave interferometer by releasing the BEC into free fall or into on-chip waveguides. For practical applications, these waveguides can be designed with self-generated offset fields in order to avoid spin flip losses.

*Speaker

Project MetaboliQs : Leveraging room temperature diamond quantum dynamics to enable safe, first-of-its-kind, multimodal cardiac imaging

Ilai Schwarzts * [1]

[1] Institute for Theoretical Physics, Ulm University, Ulm – Germany

Cardiovascular Diseases (CVDs) are the number 1 cause of death globally: more people die annually from CVDs than from any other cause. Despite emerging diagnostics tools and therapeutics, several areas of significant unmet need remain unaddressed among CVD patients. The ability to personalize cardiovascular medical care and improve outcomes, will require characterization of disease processes at a molecular level. The current state-of-the-art, e.g., Positron emission tomography (PET), does not provide detailed information about the chemical state of the tissue at a molecular level, therefore it remains difficult to accurately diagnose and confidently select appropriate therapy in many circumstances. The MetaboliQs project brings together two areas of European excellence - diamond-based quantum sensing and medical imaging. We will translate a newly developed hyperpolarization method for magnetic resonance imaging (MRI) based on the quantum dynamics of nitrogen-vacancy (NV) centers. This breakthrough quantum technology will enable previously unachievable, highly sensitive quantification of metabolic activity, paving the way for precision diagnostics and better personalized treatment of cardiovascular and other metabolic diseases. For realizing and eventually commercializing the technology, MetaboliQs brings together a world-class multidisciplinary consortium with end to end expertise - leading diamond quantum technology research institutes (Fraunhofer IAF - quantum-grade diamond growth and fabrication, HUJI - quantum sensing) and innovative companies (Element 6 - worldwide leader in synthetic diamonds, NVision - inventor of diamond-based polarization), as well as two expert users of hyperpolarized and cardiovascular MRI (TUM, ETH Zurich - first in continental Europe to conduct clinical trials of hyperpolarized MRI for cardiovascular disease) and the market leader in electron paramagnetic resonance and preclinical MRI (Bruker).

*Speaker

Quantum Absolute Sensors for Gravity measurements

Sébastien Merlet * [1], Romain Karcher * [1], Romain Caldani * [1], Kanxing Weng * [1], Franck Pereira Dos Santos * [1]

[1] LNE-SYRTE – Observatoire de Paris, Université PSL, CNRS, Sorbonne Université – France

The measurement of gravity, gravimetry, or its gradients, gradiometry, allows for static and dynamical studies of mass distributions, from local to global scales. Applications cover many disciplinary fields, such as geophysics, natural resources exploration, hydrology, geodesy, inertial navigation, fundamental physics and metrology. Gravity measurements are performed with two different classes of instruments: gravimeters, most widely used, measure the gravity acceleration, whereas gradiometers measure its gradient.
Quantum gravity sensors, based on cold atom interferometry techniques, can offer higher sensitivities and accuracies than current state of the art available technologies. Their limits in performances, both in terms of accuracy and long term stability, are linked to the temperature of the atomic cloud, in the low μK range, and more specifically, to the residual ballistic expansion of the atomic sources. To overcome these limits, we use ultracold atoms in the nano-kelvin range in our sensors.

I will first present our Cold Atom Gravimeter (CAG) used for the determination of the Planck constant with the LNE Kibble Balance. It performs continuously 3 gravity measurements per second with a demonstrated long term stability of 0.06 nano-g in 40 000s of measurement. Using ultracold atoms produced by evaporative cooling in a crossed dipole trap as a source, its accuracy, which is still to be improved, is currently at the level of 2 nano-g. This makes our CAG, the more accurate gravimeter. Then I will describe a " dual sensor " which performs simultaneous measurements of $g$and its gradient. This offers the possibility to resolve, by combining the two signals, the ambiguities in the determination of the positions and masses of the sources, offering new perspectives for applications. It uses cold atom sources for proof of principle demonstrations and will soon combine ultra-cold atomic samples produced by magnetic traps on a chip and large momentum beamsplitters. With these two key elements, the gradiometer will perform measurements in the sub-E sensitivity range in 1s measurement time on the ground (1 E = 10-9s-2). Such a level of performances opens new prospects for on field and on board gravity mapping, for drift correction of inertial measurement units in navigation, for geophysics and for fundamental physics.

*Speaker

Project ASTERIQS: Advancing Science and TEchnology thRough dIamond Quantum Sensing

Thierry Debuisschert * [1]

[1] THALES Research and Technology (TRT),Palaiseau – France

ASTERIQS will exploit quantum sensing based on nitrogen-vacancy-centres in ultrapure diamond to bring solutions to societal and economical needs for which no solution exists yet. Its objectives are to develop:

1. Advanced applications based on magnetic field measurement: a fully integrated scanning diamond magnetometer instrument for nanometer scale measurements, a high dynamics range magnetic field sensor to control advanced batteries used in electrical car industry, a lab-on-chip Nuclear Magnetic Resonance (NMR) detector for early diagnosis of diseases, a magnetic field imaging camera for biology or robotics, and an instantaneous spectrum analyser for wireless communications management
2. New sensing applications to sense temperature within a cell, to monitor new states of matter under high pressure and to sense electric fields with ultimate sensitivity;
3. New measurement tools to elucidate the chemical structure of single molecules by NMR for the pharmaceutical industry or the structure of spintronics devices at the nanoscale for a new generation of spin-based electronic devices.

To achieve these goals, the project will develop enabling tools, such as highest grade diamond material with ultralow impurity level, advanced protocols to overcome residual noise in sensing schemes, and optimized engineering for miniaturized and efficient devices.

ASTERIQS will disseminate its results towards academia and industry and educate the next generation of physicists and engineers. The consortium federates world leading European academic and industrial partners to bring quantum sensing from the laboratory to applications.

*Speaker

Using polarons for sub-nK quantum non-demolition thermometry in a Bose-Einstein condensate

Mohammad Mehboudi * [1], Aniello Lampo [2], Christos Charalambous [2], Luis A. Correa [3], Miguel-Angel Garcia-March [2], Maciej Lewenstein [2,4]

[1] Institut de Ciencies Fotoniques [Castelldefels](ICFO) – Parc Mediterrani de la Tecnologi, E-08860 Castelldefels (Barcelona), Spain
[2] Institut de Ciencies Fotoniques [Castelldefels]– Spain
[3] School of Mathematical Sciences [Nottingham]– United Kingdom
[4] Institució Catalana de Recerca i Estudis Avançats – Spain

We introduce a novel minimally-disturbing method for sub-nK thermometry in a Bose-Einstein condensate (BEC). Our technique is based on the Bose-polaron model; namely, an impurity embedded in the BEC acts as the thermometer. We propose to detect temperature fluctuations from measurements of the position and momentum of the impurity. Crucially, these cause minimal back-action on the BEC and hence, realize a non-demolition temperature measurement. Following the paradigm of the emerging field of *quantum thermometry*, we combine tools from quantum parameter estimation and the theory of open quantum systems to solve the problem in full generality. We thus avoid *any* simplification, such as demanding thermalization of the impurity atoms, or imposing weak dissipative interactions with the BEC. Our method is illustrated with realistic experimental parameters common in many labs, thus showing that it can compete with state-of-the-art *destructive* techniques, even when the estimates are built from the outcomes of accessible (sub-optimal) quadrature measurements.

*Speaker

iqClock - the route towards a portable, industry-built optical clock

Yeshpal Singh * [1], Markus Gellesch [1], Jonathan Jones [1], Kai Bongs [1]

[1] The University of Birmingham – United Kingdom

Optical clocks are frequency standards with unmatched stability. Bringing those clocks from the laboratory into a robust and compact form will have a large impact on telecommunication, geology, astronomy, and other fields. Likewise, techniques developed for robust clocks will improve laboratory clocks, potentially leading to physics beyond the standard model. To make this transition a reality, we have brought together the iqClock consortium (https://www.iqclock.eu), assembling leading experts from academia, strong industry partners, and relevant end users. We will seize on recent developments in clock concepts and technology to start-up a clock development pipeline along the TRL scale. Our first product prototype will be a field-ready strontium optical clock, which we will benchmark in real use cases. This clock will be based on a modular concept, already with the next-generation clocks in mind, which our academic partners will realize. Here, we will outline our approach towards realising this modular and portable optical lattice clock.

*Speaker

Chapter 13

Friday - 8:45-10:30 : BSCC - 4 (Platine)

Project QMICS : Quantum Microwave Communcation and Sensing

Mikko Mottonen * [1]

[1] Department of Applied Physics, Aalto University, Espoo – Finland

The mission of QMiCS is to combine European expertise and lead the efforts in developing novel components, experimental techniques, and theory models building on the quantum properties of continuous-variable propagating microwaves. QMiCS' long-term visions are (i) distributed quantum computing communication via microwave quantum local area networks (QLANs) and (ii) sensing applications based on the illumination of an object with quantum microwaves (quantum radar). With respect to key quantum computing platforms (superconducting circuits, NV centers, quantum dots), microwaves intrinsically allow for zero frequency conversion loss since they are the natural frequency scale. They can be distributed via superconducting cables with surprisingly little losses, eventually allowing for quantum communication and cryptography applications. Radar works at gigahertz frequencies because of the atmospheric transparency windows anyways. Scientifically, QMiCS targets a QLAN demonstration via quantum teleportation, a quantum advantage in microwave illumination, and a roadmap to real-life applications for the second/third phase of the QT Flagship. Beneath these three grand goals lies a strong component of disruptive enabling technology provided by two full and one external industry partner: the development of a microwave QLAN cable connecting the millikevin stages of two dilution refrigerators, improved cryogenic semiconductor amplifiers, and packaged pre-quantum ultrasensitive microwave detectors. The resulting ""enabling"" commercial products are beneficial for quantum technologies at microwave frequencies in general. Finally, QMiCS fosters awareness in industry about the revolutionary business potential of quantum microwave technologies, especially via the advisory third parties "Airbus Defence and Space Ltd" and "Cisco Systems GmbH". In this way, QMiCS helps placing Europe at the forefront of the second quantum revolution and kick-starting a competitive European quantum industry.

Microwave remote state preparation vs. quantum cryptography

Frank Deppe * [1,2,3]

[1] Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany – Germany
[2] Physik-Department, Technische Universität München, 85748 Garching, Germany – Germany
[3] Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany – Germany

*Speaker
*Speaker

Quantum communication protocols employ nonclassical correlations as a resource for an efficient transfer of quantum states [R. Di Candia *et al.*, EPJ Quantum Technol. **2**, 25 (2015)]. As a fundamental protocol, remote state preparation (RSP) aims at the preparation of a known quantum state at a remote location using classical communication and quantum entanglement. In our experiment, we use flux-driven Josephson parametric amplifiers and linear circuit elements to generate propagating two-mode squeezed (TMS) microwave states acting as quantum resource [K. G. Fedorov *et al.*, Phys. Rev. Lett. **117**, 020502 (2016); K. G. Fedorov *et al.*, Sci. Rep. **8**, 6416 (2018)]. Combined with a classical feedforward, we use these TMS states to remotely prepare single-mode squeezed states. Furthermore, we analyze the consumption of quantum discord in our experiment and interpret our results in the framework of a quantum cryptographic protocol analogous to the Vernam cipher. The authors acknowledge support from: the German Research Foundation through FE 1564/1-1; the doctorate program ExQM of the Elite Network of Bavaria; the EU Quantum Flagship project 'Quantum Microwaves for Communication and Sensing (QMiCS)' Grant Agreement No. 820505; the German Excellence Initiative via the 'Nanosystems Initiative Munich' (NIM) and the 'Munich Center for Quantum Science and Technology (MCQST)'.

PhoQuS, Photons for Quantum Simulation

Alberto Bramati * [1]

[1] Laboratoire Kastler Brossel – Sorbonne Université, Ecole Normale Supérieure de Paris - ENS Paris, CNRS : UMR8552 – France

The aim of PhoQus is to develop a novel platform for quantum simulation, based on photonic quantum fluids, realised in different photonic systems with suitable nonlinearities, allowing to engineer an effective photon-photon interaction. In such platform, we will simulate systems of very different nature, ranging from astrophysics to condensed matter. In this talk, I will discuss the main objectives of the project, present the involved teams and show the first results of the consortium.

*Speaker

Hong-Ou-Mandel effect under partial time reversal : an interference effect due to timelike indistinguishability in the amplification of light

Nicolas Cerf * [1]

[1] Université Libre de Bruxelles [Bruxelles](ULB) – Avenue Franklin Roosevelt 50 - 1050 Bruxelles, Belgium

In the usual, predictive approach of quantum mechanics, one deals with the preparation of a quantum system, followed by its time evolution and ultimately its measurement. In the retrodictive approach of quantum mechanics, one postselects the instances where a particular measurement outcome was observed and considers the probability of the preparation variable conditionally on this measurement outcome. This can be interpreted as if the measured state had propagated backwards in time to the preparer. Here, we present an intermediate picture, coined *partial time reversal*, where a composite system is propagated partly forwards and partly backwards in time. As a striking application, we focus on the simplest two-mode linear-optical component, namely a beam splitter, and show that it transforms into a two-mode squeezer under partial time reversal. More generally, by building on the generating function of the matrix elements of Gaussian unitaries in Fock basis, we prove that the multiphoton transition probabilities obey simple recurrence equations. This method applies to Gaussian unitaries effecting both passive and active linear coupling between two bosonic modes. The recurrence includes an interferometric suppression term which generalizes the Hong-Ou-Mandel effect for more than two indistinguishable photons impinging on a beam splitter of transmittance 1/2. It also exhibits an unsuspected 2-photon suppression effect in an optical parametric amplifier of gain 2 originating from the indistinguishability between the input and output photons, which we coin *timelike indistinguishability* (it is the partial time-reversed version of the usual *spacelike indistinguishability* which is at work in the Hong-Ou-Mandel effect).

M. G. Jabbour and N. J. Cerf, Multiphoton interference effects in passive and active Gaussian transformations, arXiv :1803.10734 [quant-ph](2018).

*Speaker

Project PhoG : Sub-Poissonian Photon Gun by Coherent Diffusive Photonics

Natalia Korolkova * [1]

[1] School of Physics and Astronomy, University of St Andrews, St Andrews – United Kingdom

Since the discovery of the first quantum key distribution (QKD) protocol over 30 years ago, interest and research in distributing keys to encrypt/decrypt secret messages via quantum means has rapidly expanded. The security of almost all online transactions and communications partly relies on the establishment of a symmetrical session key, in which the security of this key is reliant on computationally hard-to-solve mathematical factorisation problems.
With the imminent threat of a quantum computer, which will be able to solve these mathematical problems exponentially faster than even the most powerful classical super computers, and therefore break all current classically-encrypted data, QKD is no longer just an academic research interest. We are now at the stage where QKD systems are looking to be commercialised, offering customers information-theoretic security, guaranteed by the fundamental laws of quantum mechanics; QKD has reached a point of maturity where it is crucial to explore use-cases in order to ensure it is designed with end solutions in mind.

Within this talk, we discuss customer use-cases for both fibre-optic and satellite based QKD systems, such as telecommunications providers, the mining, oil and gas industry, the public sector, virtual private networks (VPNs) and cloud data back-ups. We deliberate the technical specifics which must be taken into consideration when commercialising such advanced technology, in both the fibre-optic and satellite communications domain; we cover distance and key rate requirements for these QKD systems, and discuss the impact that photonic losses, in the fibre and free-space circumstance, as well as atmospheric effects (in the satellite-QKD regime), have on these requirements. We also discuss other requirements necessary for the adoption of QKD as a service, such as trusted nodes, QKD protocols, and intrinsic security of these protocols, with associated limitations and benefits.

We conclude that there is a significant commercial interest in QKD, by a broad and diverse range of customers and sectors, and that there is potential for QKD to be adopted within some of these areas within the next five years, with a far greater implementation in the next ten or more years.

*Speaker

The commercial case for QKD: an analysis of use cases and implications for the performance of the underlying technology

Ryan Parker * [1]

[1] BT Research – United Kingdom

Since the discovery of the first quantum key distribution (QKD) protocol over 30 years ago, interest and research in distributing keys to encrypt/decrypt secret messages via quantum means has rapidly expanded. The security of almost all online transactions and communications partly relies on the establishment of a symmetrical session key, in which the security of this key is reliant on computationally hard-to-solve mathematical factorisation problems.
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*Speaker

D-dimensional frequency-time entangled cluster states with on-chip/fiber-based photonic systems

Michael Kues * [1], Christian Reimer [2], Stefania Sciara [3], Piotr Roztocki [3], Mehedi Islam [3], Luis Romero Cortés [3], Yanbing Zhang [3], Bennet Fischer [3], Sébastien Loranger [4], Raman Kashyap [4], Alfonso Cino [5], Sai T. Chu [6], Brent E. Little [7], David J. Moss [8], Lucia Caspani [9], William J. Munro [10], José Azãna [3], Roberto Morandotti [3]

[1] School of Engineering, University of Glasgow – United Kingdom
[2] John A. Paulson School of Engineering and Applied Sciences, (-) – Harvard University, United States
[3] Énergie Matériaux Télécommunications - INRS – Canada
[4] Engineering Physics Department, Polytechnique Montreal – Canada
[5] Department of Energy, Information Engineering and Mathematical Models, University of Palermo – Italy
[6] Department of Physics and Material Science, City University of Hong Kong – Hong Kong SAR China
[7] State Key Laboratory of Transient Optics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Science, – China
[8] Centre for Micro Photonics, Swinburne University of Technology – Australia
[9] University of Strathclyde – United Kingdom
[10] NTT Basic Research Laboratories and NTT Research Center for Theoretical Quantum Physics, NTT Corporation – Japan

Today's quantum science focuses on the realization of large-scale complex non-classical systems to e.g. enable ultra-secure communications, quantum-enhanced measurements, and computations faster than classical approaches. In this context, 'cluster states', a specific class of multi-partite entangled states, are of particular importance. Such systems are equivalent to the realization of a one-way (or measurement-based) quantum computer, where algorithms are implemented through high-fidelity measurements on the parties of the state. While two-level (i.e. qubit) cluster states have been realized so far, increasing the number of particles to boost the computational resource comes at the price of significantly reduced coherence time and detection rates, as well as increased sensitivity to noise, thus restricting the realization of discrete cluster states to a record of eight qubits. In a novel approach, the use of d-level (i.e. qudit) entangled states has the potential to address several limitations of qubit cluster states. First, the quantum resource can be increased without modifying the number of particles; second, d-level quantum states enable the implementation of highly efficient computational protocols; and third, higher dimensions reduce the noise sensitivity of the cluster states. Up till now, the realization of discrete d-level cluster states has not been demonstrated. Here, we show: i) the realization of high-dimensional cluster states based on the simultaneous entanglement-i.e. hyper-entanglement-of two photons in their time and frequency domains, ii) the ability to perform d-level one-way quantum processing operations on the states through projection measurements, and iii) that higher-dimensional forms of cluster states are more noise tolerant than lower dimensional realizations. Our approach is based on integrated photonic chips and optical fiber communication components and achieves new and deterministic functionalities. Thus,

*Speaker

our work provides an important step towards achieving powerful and noise-tolerant quantum computation in a scalable and mass-producible platform.

Chapter 14

Friday - 8:45-10:30 : Computing - 3 (Platine)

Quadrupolar Exchange-Only Spin Qubit

Guido Burkard * [1]

[1] University of Konstanz – Germany

We propose a quadrupolar exchange-only spin qubit [1]that is highly robust against charge noise and nuclear spin dephasing, the dominant decoherence mechanisms in quantum dots. The qubit consists of four electrons trapped in three quantum dots, and operates in a decoherence-free subspace to mitigate dephasing due to nuclear spins. To reduce sensitivity to charge noise, the qubit can be completely operated at an extended charge noise sweet spot that is first-order insensitive to electrical fluctuations. Because of on-site exchange mediated by the Coulomb interaction, the qubit energy splitting is electrically controllable and can amount to several GHz even in the "off" configuration, making it compatible with conventional microwave cavities.

[1]M. Russ, J. R. Petta, and G. Burkard, Phys. Rev. Lett. 121, 177701 (2018)

*Speaker

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.

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

*Speaker

Gate-Based High Fidelity Spin Readout in a CMOS Device

Matias Urdampilleta [1], David Niegemann * [2], Emmanuel Chanrion [1], Baptiste Jadot [1], Cameron Spence [2], Pierre-Andre Mortemousque [1], Christopher Bäuerle [1], Louis Hutin [3], Benoit Bertrand [3], Sylvain Barraud [3], Romain Maurand [4], Marc Sanquer [4], Xavier Jehl [4], Silvano De Franceschi [4], Maud Vinet [3], Tristan Meunier [1]

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Over the last fifty years, the CMOS (Complementary-Metal-Oxide-Semiconductor) electronics industry has been continuously scaling down transistors in size, to increase performance and reduce power consumption. Nowadays, the smallest transistors in industry achieve 5 nm features. As a result, those silicon structures tend to exhibit undesirable quantum effects for a classical transistor which appear to be new research opportunities for quantum information processing.

In particular, it is nowadays possible to trap single electron spins in silicon quantum dots and perform high fidelity quantum gates[i]. These demonstrations combined with the intrinsic properties of the silicon lattice[ii](low spin orbit and hyperfine interaction) make CMOS device an excellent candidate for scalable quantum architectures.

In this presentation, we will show how we can detect a single spin in a CMOS device thanks to an original approach which combines gate-based dispersive charge sensing and a latched Pauli spin blockade mechanism[iii]. For this purpose, we use a double quantum dot coupled to a single reservoir where one of the dot carries the spin information while the second dot is used as an ancillary dot to perform the readout.

This scalable method allows us to read out a single spin with a fidelity above 98% for 0.5 ms integration time[iv]. Moreover, we show that the demonstrated high read-out fidelity is fully preserved up to 0.5 K. This result holds particular relevance for the future co-integration of spin qubits and classical control electronics.

[i] Veldhorst, M. *et al. Nat. Nanotechnol.* **9,** 981 (2014).

[ii]Steger, M. *et al. Science* **336,** 1280 (2012).

[iii]Harvey-Collard, P. *et al. Phys. Rev. X* **8**, 021046 (2018).

[iv]Urdampilleta, M. *et al.* arXiv:1809.04584 (under review @ Nat. Nano.)

*Speaker

Circuit quantum electrodynamics with silicon spin qubits

Monica Benito * [1]

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Electron spins in silicon quantum dots are attractive systems for quantum computing owing to their long coherence times and the promise of rapid scaling of the number of dots in a system using semiconductor fabrication techniques. The control and readout of individual electron spins and the interaction of separated spin qubits via microwave frequency photons are the cornerstones of spin-based large-scale quantum technology.

The coupling of a spin to an electric field can be achieved through the combined effect of the electric-dipole interaction and spin-charge hybridization, which deteriorates the coherence properties of the spin qubit. In this work we focus on single electron spin qubits placed in silicon double quantum dots and hybridized to the charge degree of freedom via an externally applied magnetic field gradient. We predict optimal working points to achieve a strong spin-photon coupling with minimal tradeoff in coherence [1]. Our theory agrees well with recent experimental results demonstrating coherent control and dispersive readout of a single electron spin in silicon, and strong coupling between a single spin and a single microwave-frequency photon [2]. These results open a direct path towards implementing resonator-mediated two-qubit entangling gates. We calculate entangling gate fidelities both in the dispersive and resonant regime accounting for errors due to the spin-charge hybridization.

[1]M. Benito, X. Mi, J. M. Taylor, J. R. Petta, and G. Burkard, Phys. Rev. B 96, 235434 (2017).
[2]X. Mi, M. Benito, S. Putz, D. M. Zajac, J. M. Taylor, G. Burkard, and J. R. Petta, Nature 555, 599 (2018).

*Speaker

Gate-based readout for silicon spin qubits: Optimization and Scaling

Simon Schaal , Alessandro Rossi , David Ibberson , Lisa Ibberson , Virginia Ciriano , Sylvain Barraud , Jason A W Robinson , John J. L. Morton , Fernando Gonzalez-Zalba * [1]

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In the quest for scaling up silicon-based quantum computing, readout by already existing gate electrodes has gained prominence due to its reduced impact in the qubit layout and comparable sensitivities to conventional charge sensors. Gate-based sensing enables readout of spins by projective measurements using the state-dependent differential capacitance of the system [1]. Recently, single-shot readout has been achieved with this technique [2-4]but further improvements are necessary to set gate-based readout well above quantum error-correction thresholds. In this talk, I will present results that highlight the steps to optimize gate-based readout. At the device level, the dispersive signal can be enhanced by increasing the gate-coupling to the quantum system using for example high-k dielectrics and 3D thin SOI technology [5]. At the resonator level, a high loaded quality factor and good matching to the line are essential. These can be achieved by using superconducting elements and optimal circuit topologies [6,7]. Ultimately, at the electronics level, the sensitivity could be further improved by reducing the noise floor using quantum-limited Josephson parametric amplification.

Last, I will explain how gate-based readout can be combined with digital technology to read multiple quantum devices sequentially while reducing the number of input lines per qubit. I will show results on digitally-interfaced dynamic readout of transistor-based silicon quantum devices [8].

References

[1]R. Mizuta, et al. Phys. B. **95** 045414 (2017)
[2]A. West, et al. arxiv :1809.01864 (2018)
[3]P. Pakkiam, et al. arxiv:1809.01802 (2018)
[4]M. Urdampilleta et al. arxiv:1809.04584 (2018)
[5]M. F. Gonzalez-Zalba, et al. Nat. Commun. **6** 6084 (2015)
[6]I. Ahmed, et al. Phys. Rev. App. **10**, 014018 (2018).
[7]D. J. Ibberson, et al. arxiv:1807.07842 (2018)
[8]Schaal et al. Phys Rev App 9 054016 and arXiv:1809.03894 (2018).

*Speaker

Long-range spin entanglement in semiconductor quantum circuits

Baptiste Jadot * [1], Pierre-Andre Mortemousque [1], Emmanuel Chanrion [2], Arne Ludwig [3], Andreas Wieck [3], Matias Urdampilleta [2], Christopher Bäuerle [4], Tristan Meunier [2]

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Creating and manipulating entanglement between qubits is a key ingredient to exploit quantum parallelism in quantum computers, or to implement quantum teleportation and communication protocols. In semiconductor quantum circuits, long distance entanglement has already been demonstrated via the exchange of a photon, but the coupling strength remains too weak to envision any scalable implementation. An alternative method, less investigated but with important advantages for scalability, would be to shuttle the qubits themselves across the nanostructure [1, 2]. The local preparation of an entangled state, followed by a coherent transport of one qubit, provides a fast and long distance two qubits entanglement mechanism.
In this work, we demonstrate the fast and coherent transport of electron spin qubits across a 6.5 μm long channel, in a GaAs/AlGaAs laterally defined nanostructure. Using the moving potential induced by a propagating surface acoustic wave, we send sequentially two electron spins initially prepared in a spin singlet state. During its displacement, each spin experiences a coherent rotation due to spin-orbit interaction, over timescales shorter than any decoherence process. By varying the electron separation time and the external magnetic field, we observe Ramsey-like interferences which prove the coherent nature of both the initial spin state and the transfer procedure.

The sequential sending procedure allows us to quantify the entanglement between the two electron spins when they are separated by 6.5 μm, proving this fast and long-range qubit displacement is an efficient procedure to share entanglement across future large-scale structures.

[1]P.-A. Mortemousque, E. Chanrion, B. Jadot, H. Flentje, A. Ludwig, A. D. Wieck, M. Urdampilleta, C. Bauerle, and T. Meunier, arXiv:1808.06180 (2018).
[2]B. Bertrand, S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. Ludwig, A. D. Wieck, C. Bauerle, and T. Meunier, Nature Nanotechnology 11, 672 (2016).

*Speaker

Coherent displacement of individual electron spins in a two-dimensional array of tunnel coupled quantum dots

Pierre-Andre Mortemousque * [1], Emmanuel Chanrion [1], Baptiste Jadot [1], Hanno Flentje [1], Arne Ludwig [2], Andreas Wieck [3], Matias Urdampilleta [1], Christopher Bäuerle [1], Tristan Meunier [1]

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Controlling nanocircuits at the single electron spin level in quantum dot arrays is at the heart of any scalable spin-based quantum information platform. The cumulated efforts to finely control individual electron spins in linear arrays of tunnel coupled quantum dots have permitted the recent coherent control of multi-electron spins and the realization of quantum simulators. However, the two-dimensional scaling of such control is a crucial requirement for simulating complex quantum matter and for efficient quantum information processing, and remains up to now a challenge.

Here we demonstrate such two-dimensional coherent control using individual electron spins in arrays up to 9 tunnel-coupled lateral quantum dots. The demonstrated charge control with one and two electrons loaded in the dot arrays permits to explore coherent spin control and displacement. To realize this, two electrons are prepared in the coherent singlet state, and separately displaced within the quantum dot arrays. We show that the motion of the electrons is not detrimental for their spin coherence properties. Actually, the fast control of the potential landscape induces moving quantum dots, in which the electron spins, through a motional narrowing process, are effectively decoupled from the substrate nuclear spins. This work demonstrates key quantum functionalities, crucial for using two-dimensional quantum dot arrays for quantum simulation and computation.

[1]H. Flentje, P.-A. Mortemousque, R. Thalineau, A. Ludwig, A. D. Wieck, C. Bauerle, T. Meunier, Coherent long-distance displacement of individual electron spins, Nat. Comm. 8, 501 (2017).

[2]P.-A. Mortemousque, E. Chanrion, B. Jadot, H. Flentje, A. Ludwig, A. D. Wieck, M. Urdampilleta, C. Bauerle, T. Meunier, Coherent displacement of individual electron spins in a two-dimensional array of tunnel-coupled quandum dots, arXiv:1808.06180.

*Speaker

Chapter 15

Friday - 8:45-10:30 : Sensing - 3 (upper room)

Noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime

Jérôme Lodewyck * [1], Grégoire Vallet [2], Bruno R. Alves [2], Yannick Foucault [2], Rodolphe Le Targat [2]

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[2] Systèmes de Référence Temps Espace – Sorbonne Université, Centre National de la Recherche Scientifique : UMR8630, Observatoire de Paris, Institut national des sciences de lÚnivers, Institut national des sciences de lÚnivers, Institut national des sciences de lÚnivers, Institut national des sciences de lÚnivers – France

We present the successful implementation of a non-destructive detection scheme for the transition probability readout of an optical lattice clock. The scheme relies on a differential heterodyne measurement of the dispersive properties of lattice-trapped atoms enhanced by a high finesse cavity. By design, this scheme offers a 1st order rejection of the technical noise sources, an enhanced signal-to-noise ratio, and a homogeneous atom-cavity coupling. We theoretically show that this scheme is optimal with respect to the photon shot noise limit. We experimentally realize this detection scheme in an operational strontium optical lattice clock (contributing to the international atomic time scale). The resolution is on the order of a few atoms with a photon scattering rate low enough to keep the atoms trapped after detection (classical non-destructivity). This scheme opens the door to various different interrogations protocols, which improve the frequency stability by reducing the Dick effect (aliasing between the clock light frequency fluctuations and the probing cycle time), including atom recycling and zero-dead time clocks with a fast repetition rate. We finally present progress into demonstrating this detection in the quantum non-destructive regime (less than one photon scattered per atom), while featuring a detection noise smaller than the quantum projection noise for 500 atoms

*Speaker

Quantum enhanced optical measurements with twin-beams: from absorbtion estimation to ghost microscopy

Elena Losero * [1,2], Alice Meda [2], Ivano Ruo Berchera [2], Alessio Avella [2], Marco Genovese [2,3]

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[2] INRiM – Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Torino – Italy

Optical measurements are at the basis of several imaging techniques and therefore increasing their sensitivity can be of wide interest. When classical light is used the sensitivity is limited by the shot noise, that, scaling as $1/\sqrt{\mathrm{N}}$, is particularly relevant when low light intensities are used. Note that low light level can be necessary in relevant practical situations, as for investigation of biological samples. Using quantum states of light it is possible to go beyond the shot noise, approaching the ultimate quantum limit. In particular here we discuss two different imaging protocols based on photon number correlation in multi-mode twin beam state.
On one side we present recent results on the estimation of transmission/absorption coefficient with true and significant quantum enhancement, using spatially correlated multi-mode twin beams [1]. We investigate different estimators in terms of sensitivity, discussing on one side their relation with the best known strategy , but also practical issues as "hidden" assumptions related to their implementation. For example the requirement on the stability of the system is taken into account. The model presented is experimentally validated, and the best sensitivity per photon ever achieved in loss estimation experiments is demonstrated.

On the other side we focus on ghost imaging (GI). Since its first proposal by Pittman in 1995 several extensions of this protocol have been proposed. Here we focus on a technique named differential ghost imaging (DGI), originally proposed and experimentally realized with thermal light [2]. A model comparing the performances of DGI and GI using thermal or twin-beam light has been developed and will be discussed: it comes out that the role of the mean photon number per spatio-temporal mode as well as the experimental inefficiencies is crucial. Moreover, an optimization of this technique is proposed. Finally, experimental results validating the model are presented, as well as the reconstruction of a biological sample.

References:

[1]E. Losero, I. Ruo-Berchera, A. Meda, A. Avella, and M. Genovese, Unbiased estimation of an optical loss at the ultimate quantum limit with twin-beams, Scient. Rep. 8, 7431 (2018)
[2]F. Ferri, D. Magatti, L. A. Lugiato, and A. Gatti, Differential Ghost Imaging, Phys. Rev. L 104, 253603 (2010)

*Speaker

Time-continuous measurements for advanced quantum metrology

Francesco Albarelli [1], Matteo A. C. Rossi [2], Dario Tamascelli [3], Matteo G. A. Paris [3], Marco G. Genoni * [3]

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[2] University of Turku – Finland
[3] University of Milan – Italy

We present some recent results regarding the use of time-continuous measurements for quantum-enhanced metrology. In both cases we assess the estimation of a magnetic field along a known direction affecting an ensemble of N two-level atoms, i.e. the estimation of the rotation frequency for an ensemble of N qubits
First we consider an initial uncorrelated state and we show that, by continuously monitoring the collective spin observable transversal to the encoding Hamiltonian, one obtains Heisenberg scaling for the achievable precision.
In the second case, we consider an initial entangled GHZ state and independent noises acting separately on each qubit; these are in fact responsible for degrading the scaling of the estimation precision from Heisenberg to standard quantum limited. We show that continuous monitoring of all these environmental modes allows us to restore the desired Heisenberg scaling. We finally discuss the role played by the geometry of the noise affecting the qubits and the role of the efficiency of the time-continuous monitoring. References:
F. Albarelli, M.A.C. Rossi, M.G.A. Paris and M.G. Genoni, New J. Phys. 19, 123011 (2017).
F. Albarelli, M.A.C. Rossi, D. Tamascelli and M.G. Genoni, Quantum 2, 110 (2018).

*Speaker

Towards a quantum-enhanced trapped-atom clock on a chip

Mengzi Huang , Mazzoni Tommaso [1], Carlos L. Garrido Alzar [1], Jakob Reichel * [2]

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We report preliminary results of a quantum-enhanced atom chip clock. Using ultracold rubidium atoms inside an on-chip optical cavity, we investigate light-induced spin squeezing and non-destructive measurements at the 10E-13 level of relative frequency stability.

*Speaker

Overcoming resolution limits with quantum sensing

Tuvia Gefen * [1], Amit Rotem [1], Alex Retzker [1]

[1] The Hebrew University of Jerusalem – Israel

We develop a new frequency super-resolution technique for quantum probes.
We show that quantum detectors can resolve two incoherent frequencies irrespective of their separation, in contrast to what is known about classical detection schemes. In particular we study the resolution limits of quantum NMR; i.e., NMR signals recorded on a quantum probe which is typically a qubit, and propose a method to overcome resolution limits in this problem.

Resolution problems, in quantum spectroscopy and elsewhere, are characterized by vanishing distinguishably; i.e, the sensitivity to the seperation between two close frequencies vanishes as they get close enough.This results in a divergent estimation uncertainty, which imposes a fundamental limitation.

We show that by applying specific coherent control methods, that nullify the projection noise, it is possible to overcome this limitation. Hence the main idea is to overcomes the vanishing distinguishability by making the projection noise vanish as well, such that these two effects cancel each other out. We generalize these results and formulate a criterion to overcome resolution limits in a general quantum setting.

*Speaker

macQsimal - miniature atomic vapor-cell Quantum devices for sensing and metrology application

Jacques Haesler * [1]

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macQsimal will design, develop, miniaturise and integrate advanced quantum-enabled sensors with outstanding sensitivity, to measure physical observables in five key areas: magnetic fields, time, rotation, electro-magnetic radiation and gas concentration. The common core technology platform for these diverse sensors is formed by atomic vapour cells realised as integrated microelectromechanical systems (MEMS) fabricated at the wafer level.
The project consortium includes leading research groups and companies who have been pioneering many of the recent advances in the field of atomic sensing and has been assembled to cover the entire knowledge chain from basic science to industrial deployment. The objectives of macQsimal are to develop five different types of miniaturised sensors: optically pumped magnetometers, atomic clocks, atomic gyroscopes, atomic GHz/THz sensors and imagers, and lastly, Rydberg-based gas sensors.
The presentation will give an overview of the different project objectives and strategies, as well as a description of its current status. The macQsimal project has started with a patent survey and a state-of-the-art analysis and it is currently addressing the preliminary designs of the different prototypes and their corresponding atomic vapor cells.

*Speaker

Beam shaping and control in an optical fibre based atom interferometer

Mark Farries * [1], Thomas Legg [1], Artur Stabrawa [1], Nikola Prtljaga [1], Philip Henderson [1], Toby Woodbridge [1], Norman Fisher [1]

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Laboratory based atom interferometry systems can provide high sensitivity measurements of gravity, time or position. However for practical applications such as land surveys, navigation or earth observation these need to be compact and ruggedized. The telecommunications industry has proven that optical fibres provide a reliable method for realising complex photonics circuits with long life times.
We describe a system based on optical fibre coupled components with rugged performance. The system utilises mode shaped optical fibres to manipulate the beam profiles and polarisation states of beams for cooling and interfering atoms. This approach enables two beams with different diameters and polarisation states to be effectively collinear so that a single collimator/telescope can be used for both beams.

Distributed feedback semiconductor lasers are used for the beam sources with one frequency doubled and locked to a gas cell and the other offset locked to provide the tuneable cooling or interferometry wavelength. This laser, operating at 1560nm, is amplified in an erbium doped fibre amplifier and frequency doubled in a periodically poled lithium-niobate waveguide. The laser frequency is precisely controlled by a low noise feedback to the laser injection current. The output is split between 4 beams via polarisation maintaining fibre couplers and each beam is power controlled via fibre coupled acousto-optic modulators.
The all fibre-coupled system is suitable for applications such as tunnels detection in land surveys.

*Speaker

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