# 2019

CoQuS
Summer
School 2019

Book of
Abstracts

## Invited Lecturers

**Quantum Algorithms & Coding**
Bettina Heim - Microsoft Research

Within the last century there has been a remarkable progression of computing to the point where today's machines can outperform even the most brilliant minds on certain tasks. As modern processors operate at increasingly smaller scales, one might go from wondering whether computing devices of the future will be governed by the rules of quantum mechanics to wondering if those rather intriguing concepts can be leveraged to define a new way of computing. The idea of harnessing the complexity of a quantum mechanical system to predict the properties and behavior of physical systems that are too complex even for today's powerful supercomputers has inspired the concept of quantum computing long before making this idea a reality seemed feasible. Quantum computers are built upon fundamentally different rules compared to conventional computers. They hold the promise to transform many industries by revolutionizing fields like cryptography, material and chemical design, among other key areas. Due to the fundamentally different nature of not only these devices but the very concepts that form the building blocks for computations, we need to reexamine most of the fundamental mechanisms that modern computing is built on. Modern computing environments are immensely complex and advanced. The applications we interact with build on layers of abstractions that facilitate the translation of our ideas and thoughts into instructions a machine can understand and process. During this summer school I will outline some of the concepts that made modern computing possible and how they may inspire our quest to empower a quantum computing revolution. I will discuss some of the challenges that we face when conceiving the abstractions that ultimately allow us to focus on what humans are best at; generating ideas and driving innovation. I will give an introduction to Q#, the design ideas behind it, and how we hope it can enable you to developing new quantum applications. I will give a practical introduction to quantum algorithms and the Microsoft tools to run them.

**Quantum Computing in the NISQ era**
Alexandru Paler - Google

There are different quantum computing languages, frameworks and toolkits with various programming styles and target audiences. However, for the first generation of quantum computers, Google Cirq may be the most NISQ-focused from the available toolkits. Cirq is more of a low level frameworks: it allows physicists and computer scientists to control how their computation will be executed, and to specifically adapt it to the capabilities and limitations of each architecture. Cirq will be the interface to the Google cloud machine.

**Quantum metrology and many-particle entanglement in atomic ensembles**

Philipp Treutlein - University of Basel

Quantum technologies exploit entanglement to revolutionize computing, communications and measurements. This has stimulated research in different areas of physics to engineer and manipulate fragile many-particle entangled states. Progress has been particularly rapid for atoms. Thanks to the large and tunable nonlinearities and the well-developed techniques for trapping, controlling, and counting, many groundbreaking experiments have demonstrated the generation of entangled states of trapped ions, cold, and ultra-cold gases of neutral atoms. Moreover, the excellent coherence properties and controlled interactions with external forces and fields makes atoms ideal for ultraprecise sensing and time keeping. All these factors call for generating nonclassical atomic states designed for phase estimation in atomic clocks and atom interferometers, exploiting many-body entanglement to increase the sensitivity of precision measurements. In this tutorial, which is based on our recent review [1], I will give an introduction to quantum metrology with nonclassical states of atomic ensembles. Basic concepts such as the standard quantum limit of atom interferometry, spin-squeezing, phase estimation, and the Heisenberg limit will be introduced, illustrated by corresponding experiments. Moreover, I will discuss several classes of nonclassical correlations, ranging from non-separability to Einstein-Podolsky-Rosen steering and Bell correlations, and report their observation in an atomic many-particle system [2-4].

[1] L. Pezz, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Rev. Mod. Phys. 90, 035005 (2018)

[2] M. F. Riedel, P. A. Bhi, Y. Li, T. W. Hnsch, A. Sinatra, and P. Treutlein, Nature 464, 1170 (2010)

[3] R. Schmied, J. D. Bancal, B. Allard, M. Fadel, V. Scarani, P. Treutlein, and N. Sangouard, Science 352, 441 (2016)

[4] M. Fadel, T. Zibold, B. Dcamps, and P. Treutlein, Science 360, 409 (2018)

**Emulating topological phases in engineered systems**
Oded Zilberberg - ETH Zurich

Over the last couple of decades, topological phases of matter have taken a crucial role in our understanding of material properties. Interestingly, this progress in material science has led to the realization that topological properties arise due to waves (Bloch) interference in periodic structures. Consequently, topological features could be engineered in classical metamaterials of various wavelengths, including photonic, phononic, and electric circuits. In this series of talks, I will attempt to cover the main achievements of topological metamaterials, beginning from the basic concepts of topological phases of matter to the realization of engineered topological bandstructures for continuous waves.

## Company Representatives

**From Transistors to Qubits**
Andreas Fuhrer Janett - IBM - (Friday 10:30-11:30)

Current IBM quantum computing hardware is based on superconducting qubits and both hardware and software offerings are quickly growing with a vibrant community of quantum developers making use of these for their research and education. However, at IBM Research - Zurich we also look at basic properties of alternative qubit platforms and one of them, the silicon spin qubit, uses fabrication technology that is very similar to the classical CMOS transistor.

At the advent of computer science, classical computing hardware evolved from mechanical relays, vacuum tubes, bipolar transistors to field effect transistors which were eventually engineered into today's ultra-scaled devices with on the order of 109 transistors per chip. To run useful quantum algorithms on an error corrected universal quantum computer it is sometimes estimated that a similar number of qubits might be needed. Nevertheless, the path from scaling transistors to scaling qubits will be accompanied by many interesting challenges and discoveries irrespective of the chosen qubit implementation.

I'll give an overview of the different realizations of silicon spin qubits (MOS, Si/SiGe, donors) and discuss the techniques that are used to initialize, control, couple and readout spin states in a qubit. The inherent small size of silicon devices, at first sight, is a great advantage but also poses challenges in fabrication and integration of spin qubits. In the case of donor qubits this requires atomically precise placement of donors in a silicon crystal, a task that can be achieved by using scanning tunneling microscope based donor device fabrication. For traditional quantum dot devices, the electron spin in isotopically purified 28Si presents itself as an ideal isolated two-level system that does not suffer from decoherence due to nuclear spins or spin-orbit coupling effects. Furthermore, the relative isolation of the spin state may facilitate operation of spin qubits at elevated temperatures which could allow a level of co-integration with basic classical control circuits on the same chip at low temperature. I'll discuss the vision for spin-based quantum computing, the current state-of-the-art in experiment and mention some of our contributions where appropriate.

[1] F. A. Zwanenburg, A. S. Dzurak, A. Morello, M. Y. Simmons, L. C. L. Hollenberg, G. Klimeck, S. Rogge, S. N. Coppersmith, and M. A. Eriksson, Rev. Mod. Phys. 85, 961 (2013).

[2] T. D. Ladd and M. S. Carroll, Encyclopedia of Modern Optics, Elsevier, Oxford, 2018, pp. 467.

[3] X. Zhang, H.-O. Li, G. Cao, M. Xiao, G.-C. Guo, G.-P. Guo, National Science Review, 6, 32 (2018)

[4] A. Kuhlmann, V. Deshpande, L. C. Camenzind, D. M. Zumbühl, and A. Fuhrer, Appl. Phys. Lett. 113, 122107 (2018).

[5] N. Pascher, S. Hennel, S. Mueller, and A. Fuhrer, New Journal of Physics, 18, 083001 (2016).

[4] T. Skeren, N. Pascher, A. Garnier, P. Reynaud, E. Rolland, A. Thuaire, D. Widmer, X. Jehl, and A. Fuhrer, Nanotechnology, 29, 435302 (2018)

## Student Talks

Monday (10:30-12:00)

**Arbitrary High-dimensional Multi-Photons Quantum Unitary Transformations**

Xiaoqin Gao - IQOQI Vienna - (10:30-11:00)

High-dimensional quantum transformations are necessary for a multi-level quantum information system. In an optical complex quantum system, complete sets of single- and multi-photon quantum gates are necessary. In a single-photon quantum system, a variety of qubit- and qudit-gates are well-known. However, multi-photon quantum gates beyond qubits are not known. Here we present the implementations for arbitrary high dimensional multi-photons quantum unitary transformations with the orbital angular momentum of photons.

**Periodically Pulsed Quantum Light from a Superconducting Qubit Ensemble**
Elena Redchenko - Institute for Science and Technology Austria - (11:00-11:30)

Nonclassical light sources are extremely important in the fields of quantum information, quantum communication, and photonic quantum technologies. We study a driven inhomogeneous ensemble of superconducting qubits coupled to a microwave resonator. The constructive rephasing of spins in the frequency comb is predicted to result in a periodic pulse train of quantum light ($g2(t,0)<1$) which corresponds to the collective transfer of excitations from the qubit ensemble to the resonator [1]. Such periodic nonclassical pulses are interesting for a temporal synchronization in quantum memory protocols. We will present results of our ongoing experiments on periodic quantum light generation in the system of five transmon qubits capacitively coupled to a coplanar waveguide resonator.

[1] H. S. Dhar, M. Zens, D. O. Krimer, and S. Rotter, Phys. Rev. Lett. 121, 133601 (2018)

**Characteristics of Topological States in the Presence of Strong Interactions**
Patrick Wong - University College Dublin - (11:30-12:00)

Topological materials will play a key role in developing future quantum technologies, as they provide robust quantum states. However, much of the research into these materials has been focused on systems which lack electronic interactions, which are known to be important in real materials. As a step towards understanding the interplay between topology and interactions, this paper investigates the nature of the topological states of the SSH model with added local Hubbard interactions. The model is solved exactly in infinite dimensions on the Bethe lattice at zero temperature using dynamical mean-field theory with the numerical renormalization group as an impurity solver. For interactions below a critical strength, bulk gapped sites develop a power-law pseudogap density of states, while sites with topological zero-mode poles are augmented by power-law diverging quasiparticle Kondo peaks. A bulk Mott insulating phase on all sites is realized above the critical interaction strength.

## Student Talks

Wednesday (10:30-12:00)

**Overcoming noise in entanglement distribution through high-dimensional encoding**

Sebastian Ecker - IQOQI Vienna - (10:30-11:00)

The distribution of single photons over long distances is a cornerstone of practical quantum communication. However, both photon loss across the link and detection of background photons limit the distance and capacity of quantum channels. By utilizing high-dimensional encodings in spatiotemporal properties of photon pairs we overcome levels of noise which are prohibitive for qubits to be transmitted. We identify two pathways to noise resilience based on increasing the resolution of the state space on the one hand and using additional measurement bases in high dimensions on the other hand. These pathways are showcased in two photonic experiments employing energy-time entanglement and entanglement in the orbital angular momentum respectively. Both experiments demonstrate revival of entanglement which was obscured by noise and therefore pave the way towards practical quantum communication systems that are able to surpass current noise and distance limitations.

**Experimental realisation of quantum networks with trapped ions**

Peter Drmota - University of Oxford - (11:00-11:30)

Trapped ions offer an excellent platform for the implementation of quantum algorithms. The number of trapped-ion qubits that can be connected is currently limited by the spectral density of motional modes in a single trap. For large-scale quantum computing applications, interfacing many individual quantum computer modules will therefore become necessary. We present a probabilistic photonic link entangling two Sr ions trapped in physically separate systems with significantly higher rates and fidelities than previously reported. With quantum computers available on a cloud-computing basis, the question of privacy and information security arises. Blind quantum computing allows a client to perform quantum algorithms on a quantum server while hiding the details of the calculation to the server. We discuss a scheme to implement blind quantum computing experimentally via an optical fibre cable connecting a trapped-ion quantum computer with a high-speed polarisation analyser controlled by the client.

**Coupled superfluidity of binary Bose mixtures in two dimensions**

Volker Karle - Institute for Science and Technology Austria - (11:30-12:00)

We consider a two-component Bose gas in two dimensions at a low temperature with short-range repulsive interaction. In the coexistence phase where both components are superfluid, interspecies interactions induce a nondissipative drag between the two superfluid flows (Andreev-Bashkin effect). We show that this behavior leads to a modification of the usual Berezinskii-Kosterlitz-Thouless (BKT) transition in two dimensions. We extend the renormalization of the superfluid densities at finite temperature using the renormalization-group approach and find that the vortices of one component have a large influence on the superfluid properties of the other, mediated by the nondissipative drag. The extended BKT flow equations indicate that the occurrence of the vortex unbinding transition in one of the components can induce the breakdown of superfluidity also in the other, leading to a locking phenomenon for the critical temperatures of the two gases.

## Student Talks

Thursday (13:30-14:30)

**Recent Results using Quantum Kernel Methods**

Evan Peters - Institute for Quantum Computing - (13:30-14:00)

The kernel method is a simple and powerful technique for supervised learning on classical data, and recent results [1,2] show how this method can be extended to use a quantum computer. In this talk I'll share recent work (IQC/Fermilab/Google X collaboration) building on these results in which we seek to classify astronomical data, and I'll highlight the challenges of designing and optimizing variational quantum circuits for kernel classification.

[1] M. Schuld and N. Killoran, Phys. Rev. Lett. 122, 040504 (2019)

[2] V. Havlicek et al., Nature 567, 209-212 (2019)

**Quantum Advantage for probabilistic one-time programs**

Marie-Christine Rohsner - University of Vienna - (14:00-14:30)

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

## Poster Session

1. **On-chip and bidirectional conversion between superconducting microwave circuits and telecom optics**
Georg Arnold - Institute of Science and Technology Austria

2. **Evolution of a scalar field in curved spacetime: a general method**
Ana Lucia Baez-Camargo - University of Vienna

3. **229Th doped CaF2 for a nuclear clock**
Kjeld Beeks - Atominstitut, TU Wien

4. **Wavefront shaping in electron microscopy via ponderomotive scattering**
Marius Chirita - University of Vienna

5. **Optomechanics with squeezed light**
Michael Croquette - Laboratoire Kastler Brossel

6. **Magneto-transport of 2degs ultra-strongly coupled to vacuum fields**
Josefine Enkner - ETH Zurich

7. **Towards quantum optomechanics experiments at room temperature**
Jingkun Guo - Kavli Institute of Nanoscience

8. **Ultrastrong coupling circuit QED in the radio-frequency regime**
Tuomas Jaako - Atominstitut, TU Wien

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9. **Sideband ground-state cooling of graphene resonator with Rydberg atoms via vacuum forces**
Muhammad Miskeen Khan - Instituto de Plasmas e Fuso Nuclear (IPFN), Instituto Superior Tecnico

10. **Deterministic 2D cluster state generation for quantum computation**
Mikkel Larsen - Technical University of Denmark

11. **Ultracold Caesium on an Atomchip: An Atom Interferometer with Tunable Interactions**
Maximilian Lerchbaumer - Atominstitut, TU Wien

12. **Optomechanical sensor for nanoscaled and quantum thermometry**
Ferhat Loubar - Laboratoire Kastler Brossel

13. **Towards Pricing Financial Derivatives with an IBM Quantum Computer**
Ana Martin - University of the Basque Country

14. **Circular motion of a quantum impurity in a bosonic bath**
Mikhail Maslov - Institute of Science and Technology Austria

15. **Environment induced Rabi Oscillations in the Boson-Boson Model**
Yuri Minoguchi - Atominstitut, TU Wien

16. **Recent Results using Quantum Kernel Methods**
Evan Peters - Institute for Quantum Computing, University of Waterloo

17. **Realisation of a photonic CNOT gate using exclusively straight waveguides**
Rene Pollmann - Universitat Paderborn

18. **Strongly Correlated Photon Transport in a Waveguide with Weakly Coupled Emitters**
Adarsh Prasad - Atominstitut, TU Wien

19. **Quantum Advantage for probabilistic one-time programs**
Marie-Christine Roehsner - University of Vienna

20. **Quantum Thermal Machines with Cold Atoms**
Joao Sabino - Atominstitut, TU Wien

21. **Floquet approach to the Dicke Time Crystal**
Akitada Sakurai - National Institute of Informatics

22. **Study I-V Characteristics Of Resonant Tunneling Diodes using Non-equilibrium Green's function (NEGF)**
Sami Sherchan - Prithvi Narayan Campus, Tribhuvan University

23. **Characteristics of Topological States in the Presence of Strong Interactions**
Patrick Wong - University College Dublin

24. **Engineering Strongly Correlated States in Bose Einstein Condensate using Optimal Control Theory**
Tiantian Zhang - Atominstitut, TU Wien