WILHELM UND ELSE HERAEUS-STIFTUNG

662. WE-Heraeus-Seminar

Quantum Networks – from building blocks to applications

February 5-7, 2018
at the Physikzentrum Bad Honnef/Germany

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. By German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and scope of the 662. WE-Heraeus-Seminar:

Quantum networks define the art of communication based on non-classical systems. They promise unique opportunities across a range of intellectual and technical frontiers. For example, quantum cryptography networks can be used for maximally secure communication and quantum networks may aid the realization of large-scale quantum computers and quantum simulators.

A variety of implementations was proposed and realized in the past years and commercial manifestations are expected in the next few years. This seminar will bring together experts and early career researchers from different communities in order to discuss the prospects and challenges of merging their fields within a joint research effort on quantum networks.

Scientific Organizers:

Prof. Christoph Becher	Universität des Saarlandes Saarbrücken / Germany E-mail: christoph.becher@physik.uni-saarland.de
Dr. Ilja Gerhardt	Universität Stuttgart Stuttgart / Germany E-mail: ilja@quantumlah.org
Dr. Janik Wolters	Universität Basel Basel / Switzerland E-mail: janik.wolters@unibas.ch

Program

Program

Sunday, February 4, 2018

17:00 – 21:00	Registration	
18:00	*DINNER*	

Monday, February 5, 2018

08:00	*BREAKFAST*	
09:00 – 09:05	Scientific organizers	**Welcome words**

Chair: Wenjamin Rosenfeld

09:05 – 09:50	Oliver Benson	**Efficient photon collection & conversion from single solid-state quantum emitters**
09:50 – 10:35	Tracy Northup	**Quantum network interfaces with trapped ions in cavities**
10:35 – 10:55	*COFFEE BREAK*	

Chair: Janik Wolters

10:55 – 11:40	Nicolas Sangouard	**Certification of quantum networks from Bell's theorem**
11:40 – 12:25	Rinaldo Trotta	**GaAs quantum dots for quantum networking**
12:25 – 12:45	Alexander Kubanek	**Towards quantum networks based on color center in diamond**
12:45 – 12:55	**Conference Photo** (in the front of the lecture hall)	
12:55	*LUNCH*	

Program

Monday, February 5, 2018

Chair: Florian Kaiser

14:15 – 15:00	Aymeric Delteil	**Quantum networks based on spin-photon interface in quantum dots**
15:00 – 15:45	Fedor Jelezko	**Diamond light matter quantum interface**
15:45 – 16:15	*COFFEE BREAK*	

Chair: Andreas W. Schell

16:15 – 17:00	Jürgen Eschner	**Single-photon - single-atom quantum interfaces**
17:00 – 17:45	Robert Thew	**Path entangled quantum networks**
17:45 – 18:25	Klaus D. Jöns Luca Francaviglia Hamidreza Siampour	**Sience Slam**
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:30	**Poster Session 1**	

Program

Tuesday, February 6, 2018

08:00	*BREAKFAST*	
Chair: Vincenzo D'Ambrosio		
09:00 – 09:45	Jens Eisert	**Towards a theory of quantum networks**
09:45 – 10:30	Harald Weinfurter	**Event-ready loophole free Bell tests and beyond**
10:30 – 10:55	*COFFEE BREAK*	
Chair: Stefanie Barz		
10:55 – 11:40	Christoph Marquardt	**Worldwide secure communication - quantum key distribution in space and on ground**
11:40 – 12:25	Christian Kurtsiefer	**Atom-light interaction in the strong focusing regime**
12:25 – 12:45	David Hunger	**Towards cavity-enhanced detection of single rare earth ions**
12:45	*LUNCH*	

Program

Tuesday, February 6, 2018

Chair: Christoph Becher

14:15 – 15:00	Christine Silberhorn	**Integrated devices for quantum communication systems**
15:00 – 15:45	Hugues de Riedmatten	**Photonic quantum state transfer between disparate quantum nodes**
15:45 – 16:15	*COFFEE BREAK*	

Chair: Costanza Toninelli

16:15 – 17:00	Michael Köhl	**Interconnecting trapped ions with optical fiber cavities**
17:00 – 17:45	Joshua Nunn	**Noise-free quantum memory at room temperature**
17:45 – 18:05	Eden Figueroa	**A quantum network of room temperature quantum memories**
18:05 – 18:25	Zhangchao Ma	**Quantum-safe internet based on service-oriented quantum key distribution network**
18:25 – 18:45	Heather Partner	**Inside the editorial process at *nature communications***
19:00	*DINNER*	
20:00	**Poster Session 2**	

Program

Wednesday, February 7, 2018

08:00	*BREAKFAST*	
Chair: Ilja Gerhardt		
09:00 – 09:45	Glenn Solomon	**Simultaneous, full characterization of a single-photon state**
09:45 – 10:30	Costanza Toninelli	**Organic molecules for quantum technologies: State of the art and future prospects**
10:30 – 10:55	*COFFEE BREAK*	
Chair: Tobias Heindel		
10:55 – 11:15	Robert Löw	**Nonlinear optics with hot Rydberg atoms**
11:15 – 11:35	Andreas Reiserer	**Quantum networks with spins in cavities**
11:35 – 11:55	Val Zwiller	**Nano building blocks for quantum networks**
11:55 – 12:10	Scientific organizers	**Conclusion / Award ceremony**
12:15	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday morning

Posters

Posters

Marco Avesani	**A novel ultrafast source-device-independent QRNG**
Stefanie Barz	**Classical multiparty computation using quantum resources**
Julia Benedikter	**Cavity-enhanced single photon source based on the silicon vacancy centre in diamond**
Matthias Bock	**High-fidelity entanglement between a trapped ion and a telecom photon via quantum frequency conversion**
Florian Böhm	**SiO_2 on Si photonic platform with ultra-low intrinsic fluorescence for integrated single photon emitters**
Alexander Bruns	**Experimental demonstration of composite stimulated Raman adiabatic passage**
Gianni Buser	**Simple atomic quantum memory suitable for semiconductor quantum dot single photons**
Efe Büyüközer	**Piezoelectric tuning of quantum photonic circuits**
Luca Calderaro	**Three-observer Bell inequality violation on a two-qubit entangled state**
Xing Chen	**Single photon randomness based on a defect center in diamond**
Michal Dąbrowski	**Certification of high-dimensional entanglement and EPR-steering with atomic quantum memory**
Vincenzo D'Ambrosio	**Tunable two-photon quantum interference of structured light**

Posters

Karsten Dideriksen	**Long-lived non-classical correlations for scalable quantum repeaters at room temperature**
Gabriel Éthier-Majcher	**Improving a solid-state qubit through an engineered mesoscopic environment**
Helmut Fedder	**Enabling quantum technology - time tagging and fast feedback loops with FPGAs**
Luca Francaviglia	**Redshift of single-photon emitters in nanowires for quantum storage with Rubidium atoms**
Robert Garthoff	**Increasing photon collection efficiency for long-distance entanglement of atoms**
Johannes Görlitz	**Coherent control and wave mixing in a thin ensemble of silicon vacancy centers in diamond**
Samuel Gyger	**SNSPD detectors for on-chip quantum optics**
Marcel Hain	**Stopped light at high storage efficiency in a $Pr^{3+}:Y_2SiO_5$ crystal**
Joshua Jing Yan Haw	**Measurement-based heralded hybrid linear amplification for quantum communication**
Tobias Heindel	**Accessing the dark exciton spin qubit in deterministic quantum-dot microlenses**
Tom Hiemstra	**Quantum interference of frequency-multiplexed photons**
Klaus D. Jöns	**Two-photon interference from remote quantum emitters**

Posters

Florian Kaiser	**Quantum frequency conversion for photonic polarisation qubits: Towards interconnected quantum information devices**
Benjamin Kambs	**Remote two-photon interference at 1550 nm after quantum frequency conversion of quantum dot photons: II. Frequency conversion and spectral correlation**
Sejeong Kim	**Bright and directional site-controlled quantum dots**
Evgenii Knyazev	**Quantum tomography enhanced through parametric amplification**
Tim Kroh	**Semiconductor quantum dots as photon sources in quantum networks**
Thomas Lettner	**Bright and tunable on-demand sources for quantum optics**
Benjamin Merkel	**Towards an efficient quantum memory at telecom wavelength**
Roberto Mottola	**Atomic quantum memory in the Paschen-Back regime**
Chris Müller	**Quantum interference with frequency-locked dissimilar light sources**
Kai Müller	**Generation of single-photon and two-photon pulses from a quantum two-level system**
Niko Nikolay	**Localized modes in leaky dielectric nanoresonators: A general optimization strategy for photon extraction**
Belinda Pang	**Reciprocity between information gained and lost in gravitational wave detection**

Posters

Michal Parniak	**Memory-enabled source of multimode quantum light**
Daniel Riedel	**Deterministic enhancement of coherent photon generation from a nitrogen-vacancy centre in ultrapure diamond**
Dylan Saunders	**Experimental demonstration of non-bilocal quantum correlations**
Eduard Sauter	**Phonon mediated spin injection in p-doped silicon**
Andreas W. Schell	**Hybrid assembly of elements for quantum networks**
Alexander Schmidt	**Quantum coins and nano sensors: Development of unforgeable diamond money**
Peter Schnauber	**Deterministic integration of QDs into on-chip MMI couplers via in-situ electron beam lithography**
Eva Schöll	**Violation of Bell's Inequality with a nanowire quantum dot**
Lucas Schweickert	**Unprecedented purity of single-photons**
Hamidreza Siampour	**On-chip plasmonic cavity-enhanced spontaneous emission rate at the zero-phonon line**
Bernd Sontheimer	**Second order correlation measurements of quantum emitters in hexagonal boron nitride and their implications on the underlying level system**
Ashwyn Srinivasan	**Advanced Germanium devices for optical interconnects**
Tim van Leent	**Towards heralded entanglement of single atoms over long distances**

Posters

Francesco Vedovato	**Wheeler's delayed-choice experiment in space**
Ephanielle Verbanis	**Heralded path entanglement in quantum networks**
Aitor Villar	**Generation of entangled photons in a novel critically phase-matched source design**
Hüseyin Vural	**Two-photon interference in an atom-quantum dot hybrid system**
Jonas H. Weber	**Remote two-photon interference at 1550 nm after quantum frequency conversion of quantum dot photons: I. Two-photon interference measurements and temporal correlation**
Thomas Weidner	**Prolongation of coherence time in Eu: YSO by ZEFOZ and dynamical decoupling**
Christian Weinzetl	**Colour centres in diamond for strong and fast light-matter interactions**
Lorenz Weiss	**Coupling individual Erbium ions to single telecom photons**
Matthias Widmann	**Silicon carbide for quantum applications**
Katharina Zeuner	**Design of a bright quantum dot source of single photons at telecom wavelengths**

Abstracts of Talks

(in chronological order)

Efficient Photon Collection & Conversion from Single Solid-State Quantum Emitters

A. Ahlrichs[1], F. Böhm[1], T. Kroh[1], C. Müller[1], N. Nikolai[1], and O. Benson[1]

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A crucial functionality of any quantum network is the efficient conversion of stationary and flying qubits. Whereas numerous quantum systems have been employed as stationary qubits, photons are the only possible carriers for flying qubits. The efficiency of conversion has intrinsic limitations given by, e.g., internal quantum yield of the stationary system or its spectral purity. However, there is also the purely classical problem of coupling to special guided or directed optical modes or the conversion to other frequencies (e.g. the telecom band).

In this presentation we address the issue of the conversion of stationary qubits in solid-state emitters such as quantum dots or defect centers in diamond. In one part we discuss strategies to employ efficient photon coupling of light from defect centers in diamond via dielectric or plasmonic antenna structures [1,2] as well as coupling to optical fibers [3]. In a second part we report on our efforts to efficiently convert photons from defect centers and quantum dots in the telecom band [4].

References

[1] "Wiring up pre-characterized single-photon emitters by laser lithography", Q. Shi, B. Sontheimer, N. Nikolay, A.W. Schell, J. Fischer, A. Naber, O. Benson, M. Wegener, Sci. Rep. 6, 31135, (2016).
[2] "Quantum emitters coupled to circular nanoantennas for high brightness quantum light sources", H. Abudayyeh and R. Rapaport, Quant. Sci. and Technol., 034004 (2017).
[3] "Fiber-Coupled Diamond Micro-Waveguides toward an Efficient Quantum Interface for Spin Defect Centers", M. Fujiwara, O. Neitzke, T. Schröder, A. W. Schell, J. Wolters, J. Zheng, S. Mouradian, M. Almoktar, S. Takeuchi, D. Englund, and O. Benson, ACS Omega 2, 7194-7202 (2017)
[4] "Heralded wave packet manipulation and storage of a frequency-converted pair photon at telecom wavelength", T. Kroh, A. Ahlrichs, B. Sprenger, and O. Benson, Quant. Sci. Technol. 2, 034007 (2017)

Quantum network interfaces with trapped ions in cavities

D. A. Fioretto[1], K. Friebe[1], P. Jobez[1], M. Lee[1], F. R. Ong[1], K. Schüppert[1], M. Teller[1], R. Blatt[1,2] and T. E. Northup[1]

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One promising approach to quantum networks is based on laser-cooled trapped ions in optical cavities, in which the cavity provides a coherent interface between single atoms and single photons. Such an interface enables the transfer of quantum information from ions onto photons for distribution over optical channels, and from photons onto ions for storage and processing.

I will present probabilistic and deterministic realizations of a quantum network interface, based on ion-photon entanglement [1] and ion-photon state transfer [2]. This context will allow us to examine, on the one hand, the strengths of the ion-cavity implementation, including capabilities for high-fidelity gate operations and coherent light-matter interactions. On the other hand, as with all experimental realizations, these experiments face significant challenges on the road to a scalable multi-node network, such as decoherence in the ion trap and scattering and absorption losses of photons in the cavity and along optical channels. I will discuss approaches to address these challenges, including the use of decoherence-free subspaces [3] and adiabatic passage [4].

References

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[2] A. Stute et al., Nature Photon. **7**, 219 (2013)
[3] M. Zwerger et al., Quantum Sci. Technol. **2**, 044001 (2017)
[4] B. Vogell et al., Quantum Sci. Technol. **2**, 045003 (2017)

Certification of quantum networks from Bell's theorem

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Device-independent certification aims to guarantee that a given device behaves as instructed without any knowledge of its internal working. It relies on Bell's theorem, which is no longer of purely fundamental interest but is leading to unexpected applications, including the characterization of quantum many-body systems [1]-[2], the certification of random number generators [2]-[3] or quantum key distribution protocols [5].

In this talk, I will show how Bell's theorem can be used to certify all the components of quantum computers that are used to store, transfer and process quantum information. Our certification methods are very robust to experimental noise and can be readily used to certify that today's devices can be used in tomorrow's quantum networks.

References

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GaAs Quantum Dots for Quantum Networking

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Nowadays, the majority of quantum optics experiments involving semiconductor-based quantum emitters are performed with Stranksi-Krastanow InGaAs quantum dots (QDs). This material system has been instrumental in the fabrication of near-optimal single photon sources and it is considered to be an "established choice". However, the performances of InGaAs QDs as sources of entangled photons have not yet reached the levels required for quantum networking.

In this talk, I will focus on a system that has received limited attention so far: GaAs QDs grown via droplet etching/epitaxy. After a brief introduction on the general properties of these QDs, I will show how they can be easily integrated onto semiconductor-piezoelectric devices capable of reshaping their emission properties [1, 2]. Then, I will demonstrate that under two-photon resonant excitation GaAs QDs can generate pure single photons [3], and highly indistinguishable entangled photon-pairs [4, 5] with concurrence larger than 97% [6]. Finally, I will present our first advanced quantum optics experiments performed with these QDs: I will show quantum teleportation using single and entangled photons emitted by the very same QD [7], and discuss two-photon interference experiments performed with two QDs located in different cryostats [8]. A discussion on future perspectives will conclude the talk.

References

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[2] X. Yuan, *et al.*, arXiv:1710.03962 (2017)
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[4] D. Huber, *et al.*, Nature Communications **8**, 15506 (2017)
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Towards Quantum Networks based on color center in diamond

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Implementing efficient, highly controllable light-matter interfaces is essential to realizing the goal of solid-state quantum networks. The nitrogen-vacancy (NV) center in diamond is a promising candidate for such interfaces due to favorable properties, such as long coherence times or single shot readout capabilities. Creating optical links between remote NV centers was an outstanding challenge until the recent demonstration of photon-mediated spin-spin entanglement between NV centers separated by three meters. I will present robust control of two remote NV centers demonstrating Hong-Ou-Mandel interference to verify the indistinguishability of photons produced by remote NV centers. The NV center's application as quantum register depends on the ability to resonantly drive closed cycling transitions and closed lambda transitions with high fidelity. The fidelity can be degraded by phonon-induced mixing within the excited state manifold, which can provide unwanted non-radiative decay channels. I will present detailed investigation of phonon-induced mixing mechanism. Besides the importance to control phonon processes for applications of the NV center in Quantum Information the NV center's broad range of applications as sensors relies on the ability to initialize and readout the electronic state with off-resonant laser light. Both, initialization and read out, rely on an inter-system crossing (ISC) process into a metastable state, a phonon-assisted shelving process that has not been fully explained. We have measured the ISC rate for different excited states and developed a model that unifies the phonon-induced mixing and ISC mechanisms.

Finally, I will give a summary of recent developments with other color centers in diamond, in particular, the Silicon-Vacancy center and the Germanium-Vacancy center in bulk diamond and nanodiamonds and discuss potential applications.

References

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Quantum networks based on spin-photon interface in quantum dots

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Entanglement plays a central role in fundamental tests of quantum mechanics as well as in the burgeoning field of quantum information processing. Particularly in the context of quantum networks and communication, some of the major challenges are the efficient generation of entanglement between distant stationary (spin) qubits, and the transfer of information from flying (photon) to stationary qubits. In this talk, I will present such experimental implementations achieved in our team with semiconductor self-assembled quantum dots (QDs).

I will present the realization of heralded entanglement between two semiconductor QD hole spins separated by 5 m. The protocol relies on single photon interference of Raman scattered light from both dots [1]. A photon detection projects the system into a maximally entangled state. The efficient spin-photon interface provided by QDs [2,3] allows us to reach a rate of 2300 entangled spin pairs per second [4], three orders of magnitude higher than prior experiments with other physical systems [5].

I will also report on other recent experimental results such as the demonstration of heralded absorption of single photon qubits –generated from a neutral quantum dot– by a single-electron charged quantum dot 5m away. When the electron spin is initially prepared in a superposition state, our scheme realizes photon-to-spin quantum state transfer, as evidenced by the strong spin-photon correlations we measured [6].

These results extend or supplement previous demonstrations in single trapped ions or neutral atoms, in atom ensembles and nitrogen-vacancy centres to the domain of artificial atoms in semiconductor nanostructures that allow for on-chip integration of electronic and photonic elements, which has the major advantage of fast spontaneous emission and efficient photon extraction, leading to much higher success rates. This work lays the groundwork for the realization of quantum repeaters and quantum networks on a chip.

References

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Diamond light matter quantum interface

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Applications in quantum communications require the ability to connect the state of long-living matter qubits to optical photons for generation of entanglement over long distances. Here we discuss a novel quantum interface connecting quantum states of optical photons and spins in diamond. Among many colour centres in diamond, the negatively charged silicon-vacancy (SiV) and germanium-vacancy (GeV) centre stand out due to its desirable optical properties. In particular, near transform-limited photons can be created with high efficiency due to the strong zero-phonon line emission that constitutes~70% of the total emission. SiV and GeV centers can also be created with a narrow inhomogeneous distribution that is comparable to the transform limited optical line width. These optical properties, due to the inversion symmetry of the system, which suppresses effects of spectral diffusion, recently enabled demonstration of two-photon interference from separated emitters that is a key requirement for many quantum information processing protocols. Interfacing coherent optical transitions with long-lived spin qubits will be the main topic of this talk. Prospects for realizing coherent quantum registers based on optically controlled GeV centers will be discussed

Single-photon - single-atom quantum interfaces

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We are developing a comprehensive set of experimental tools, based on single photons and trapped single ions, that enable controlled generation, storage, transmission, and conversion of photonic qubits in quantum networks. Specifically, we implemented a programmable atom-photon interface, employing controlled quantum interaction between a single trapped $^{40}Ca^+$ ion and single photons [1,2]. Depending on its mode of operation, the interface serves as a bi-directional atom-photon quantum state converter (receiver and sender mode), as a source of entangled atom-photon states (entangler mode), or as a quantum frequency converter of single photons [3,4] (converter mode). It lends itself particularly to integrating ions with single photons or entangled photon pairs from spontaneous parametric down-conversion (SPDC) sources [5,6]. As an experimental application of the receiver mode, we demonstrate the transfer of entanglement from an SPDC photon pair to atom-photon pairs with high fidelity [7]. It is realized by heralded absorption and storage of a single photonic qubit in a single ion. We also extend our quantum network toolbox into the telecom regime by entanglement-conserving quantum frequency conversion [8] of photons that are generated by the interface in entangler mode [9].

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Path Entangled Quantum Networks

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We will discuss how path entanglement is not only one of the simplest forms of entanglement, but also, one of the most important for entanglement-based quantum networks. This will start with the basic ideas about how we generate this and a novel approach to its measurement. We will briefly talk about some of the photonic building blocks we have developed for exploring these questions. Along the way we will also present several approaches to certifying this, along with discussing some of the challenges of certifying large multipartite networks. We will briefly present several experimental results in this context as well as recent work on using heralded photon amplifiers to overcome loss when distributing entanglement. Finally, we will present ongoing work dealing with many of the practical issues of distributing entanglement in real world networks.

References

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Towards a theory of quantum networks

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Quantum networks promise new modes of quantum communication beyond point-to-point applications, with the idea of a quantum internet providing a guiding vision. This talk will be concerned with conceptual and theoretical questions related to quantum networks. We will be concerned with how to manipulate multi-partite quantum information in quantum networks, addressing old questions in the theory of multi-partite entanglement (1). We will then turn to multi-partite repeaters and notions of quantum routing in quantum networks (2). If time allows, we will finally investigate how components of quantum networks can be certified (3). We will claim that in order to identify the full potential of quantum networks, more theory work needs to be done.

References

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2. Quantum routing, F. Hahn, A. Pappa, J. Eisert, in preparation.
3. Recovering quantum gates from few average gate fidelities, I. Roth, R. Kueng, S. Kimmel, Y.-K. Liu, J. Eisert, and M. Kliesch, in preparation.

Event-ready loophole free Bell tests and beyond

W. Rosenfeld[1,2], D. Burchardt[1], R. Garthoff[1], T. Hummel[1], T. van Leent[1], N. Ortegel[1], M. Rau[1] K. Redeker[1], H. Weinfurter[1,2]

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An experimental test of Bell's inequality allows to test the validity of local-realistic descriptions of nature by measuring correlations between distant systems. While such tests are conceptually simple, there are strict requirements concerning the detection efficiency of the involved measurements, as well as the enforcement of space-like separation between the measurement events. Only recently both loopholes could be closed simultaneously.

Here we present our approach based on combining heralded entanglement of atoms separated by 398 m with fast and efficient measurements of the atomic spin states. We obtain a violation $S=2.22 \pm 0.033 > 2$, which allows us to refute the hypothesis of local-realism with very high significance [1]. With entanglement swapping employed for entangling remote quantum memories, this experiment represents a quantum relay, the basic element of quantum repeater networks, yet, a lot remains to be done, still.

The ability to test for local hidden variables can now be employed to design quantum communication protocols evaluating possible information about the communication. We discuss the benefits and requirements for an experiment implementing such so-called device-independent communication schemes.

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Worldwide secure communication – quantum key distribution in space and on ground

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Worldwide secure communication is important for an increasingly connected international society. Currently deployed cryptographic methods are at risk by future attacks e.g. by quantum computer algorithms. Quantum Key Distribution will offer provable long-term security for critical infrastructure and secure communication. Today several approaches are being developed. I will review concepts that combine ground-based and space optical quantum communication links to achieve world-wide coverage.

On ground quantum repeater infrastructure will enable to transfer fragile quantum states over longer distances. For this purpose versatile sources of quantum states that are compatible to other components like quantum memories are needed.
I will present a compact source of photon-pairs and squeezed light based on efficient parametric down conversion in a triply resonant whispering-gallery resonator (WGR) made out of lithium niobate [1]. The central wavelength of the emitted light can be tuned over hundreds of nanometers and allows for precise and accurate spectroscopy with heralded single photons of tunable bandwidth.

Optical free space communication is a reliable means to transmit classical and quantum information. Free space links offer ad-hoc establishment in intra-city communication, air-to-ground or satellite-to-ground scenarios. Quantum communication in space offers a fast route to global coverage [2]. I will discuss current activities, including the development of quantum key distribution with coherent optical communication in satellite systems, employing both discrete and continuous variable detection.

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Atom-light interaction in the strong focusing regime

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Understanding the interaction between atoms or individual emitters and photons at the single photon level is important for implementing elementary quantum gates that use optical photons to transfer information between different microscopic systems in a quantum network. To arrive at a sizable interaction of individual photons with atoms or atom-like systems, the most common technique to increase the electrical field at the location of an atom is to employ optical cavities or other resonant structures with a small effective mode volume for the electromagnetic field.

A complementary method to arrive at a small effective mode volume of an electromagnetic field is to use strong focusing. This localizes the electromagnetic filed in a small region of space, and permits significant interaction between a single atom and single photons. In this presentation, we report on recent progress in our group on increasing this interaction in a propagating field configuration using large numerical aperture lenses [1], an electric field geometry borrowed from 4-Pi microscopy, where single-atom extinction over 36% has been observed [2], and the electrical field in a near-concentric resonator geometry [3], which may permit very high interaction strengths [4].

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Towards cavity-enhanced detection of single rare earth ions

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Rare earth ions doped into solids provide outstanding optical and spin coherence properties, which renders them as promising candidates for optically adressable quantum memories and multi-qubit registers. However, due to the dipole-forbidden nature of the coherent transitions, they couple only weakly to optical fields. This limits most experiments to macroscopic ensembles, where inhomogeneous broadening complicates and limits quantum control.

Here we present an approach to get efficient access to individual ions or small ensembles by coupling them to a high-Finesse optical microcavity. We employ fiber-based Fabry-Perot cavities [1] with high finesse and a free-space mode volume as small as a few λ^3 to achieve substantial Purcell enhancement. This offers the potential to boost the spontaneous emission rate by several orders of magnitude (up to 10^4), thereby making the weak transitions bright.

We report on the current status of our experiment, where we investigate $Eu3^+$:Y_2O_3 nanocrystals [2] coupled to a cavity in a cryogenic environment.

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Integrated devices for quantum communication systems

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Recent achievements in the area of integrated quantum optics and quantum information processing have shown impressive progress for the implementation of linear circuits based on monolithic waveguide structrues. However, most experiments are based on $\chi^{(3)}$-media, such as glas, silicon-on insulator or silica-on-silicon. In these platforms the implementation of highly efficient sources, frequency converters and fast active phase shifters and modulators pose severe challenges.The use of advanced waveguide structures, which harness a $\chi^{(2)}$–non-linearity, allows for the realization various devices with multiple functionalites. These include single- and multi-channel sources with extraordinary brightness, quantum frequency conversion with tailored spectral-temporal properties, and complex circuitries comprising degenerate pair generation in orthogonal polarization, linear elements, and active elements such as polarization rotators or an electro-optically controllable time delay. Here we present our latest progress for the implementation of integrated devices based on $\chi^{(2)}$–media for quantum circuits and quantum communication systems.

Photonic Quantum State Transfer between Disparate Quantum Nodes

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The interconnection of fundamentally different quantum platforms via photons is a key requirement to build future hybrid quantum networks. Such heterogeneous architectures hold promise for more powerful capabilities than their homogeneous counterparts, as they would benefit from the individual strengths of different quantum matter systems.

In this talk, we report on interfacing a cold atomic ensemble of rubidium atoms with a praseodymium ion-doped crystal [1]. The cold atom cloud, besides being an excellent quantum memory (QM) and single photon source [2], also gives access to quantum processing via Rydberg excitation [3]. The crystal offers multiplexed long-lived quantum state storage in a solid-state environment [4]

In our experiment, we demonstrate storage in the solid-state memory of a paired single photon, emitted from the atomic cloud. As both systems exhibit very different optical transitions, we apply cascaded frequency conversion techniques to bridge the wavelength gap between them. Moreover we transfer the quantum information using a single photon at telecom wavelength, favorable for long distance communication in optical fibers. We demonstrate that non-classical correlations are preserved through frequency conversion, storage and retrieval. Finally, we show the transfer of a single-photon time-bin qubit between the two fundamentally different QM systems with a conditional fidelity of 85%, surpassing the classical threshold. These results can also be extended to other types of quantum nodes and open the way to combine quantum nodes with different functionalities.

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Interconnecting trapped ions with optical fiber cavities

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Noise-free quantum memory at room temperature

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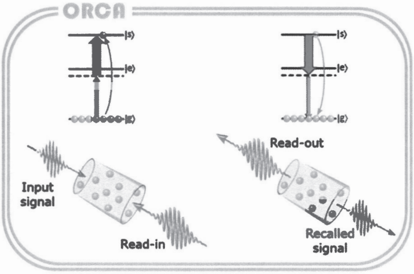
Optical memories are critical for scalable quantum networking [1]. Memory efficiencies and storage times have been improving, but protocols that are noise-free are needed to preserve quantum properties [2]. A technically simple design is also desirable because thousands of memories will be needed in a real-world quantum network.



Here we introduce light storage by off-resonant cascaded absorption (ORCA), which combines a broad acceptance bandwidth with noiseless operation at room temperature [3]. In the ORCA memory, a control pulse mediates the conversion of an incident signal pulse into a collective orbital excitation in a warm atomic vapour. Unlike Λ-type memories, the storage bandwidth is not limited by an atomic hyperfine splitting. Furthermore collisional fluorescence, thermal Raman and four-wave mixing noise [2] are all absent because the storage state lies energetically above the virtual level induced by the control field.

To test these predictions we demonstrated the ORCA memory on the $6S_{1/2}$-$6P_{3/2}$-$6D_{5/2}$ line in Cs vapour with GHz-bandwidth heralded single photons at 852 nm and confirmed that their measured autocorrelation of $g^{(2)} = 0.02$ was unchanged after storage and retrieval. Extended storage times have recently been shown in Rb [4].

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A quantum network of room temperature quantum memories

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Progressing quantum technologies to room temperature operation is key to unlock the potential and economic viability of many-device quantum networks. Along these lines, warm atomic ensembles are a viable alternative to cold atoms setups or cryogenically cooled condensed matter systems.

Here we report our progress towards building a prototypical quantum network, containing several high duty cycle room-temperature quantum memories interconnected using high rate entanglement sources. We have already demonstrated important capabilities such as, (i) portable warm 87 Rb atomic vapor quantum memories operating in a ultralow-noise regime of operation with qubit storage fidelities > 98% [1], (ii) memory-built-in photon-shaping techniques necessary to interface several quantum memories efficiently [2] and (iii) a functional elementary quantum network combining random polarization qubits, a free-space quantum communication channel, an ultra-low noise quantum memory and a qubit decoder, already capable of performing the BB84 quantum cryptography protocol with small quantum bit error rates [3].

Furthermore, we have finished the implementation of a cryptographic network containing two quantum memories, receiving, storing and transforming randomly polarized photons, aimed to realize the memory-assisted measurement device independent QKD protocol [4]. Recently we have also finished the expansion of this elementary network by adding two more quantum memories and two SPDC-based polarization entanglement sources tuned to rubidium transitions. This body of works suggest that an elementary quantum repeater node using polarization entanglement swapping mediated by room temperature quantum memories is already within experimental reach.

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Quantum-safe Internet based on Service-oriented Quantum Key Distribution Network

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The fast development of quantum computer poses significant threat to today's cyber security. There are three routes to achieve quantum-safe internet. First, post-quantum cryptography which relies on new complexity-based asymmetric algorithms, is easy to deploy, but it cannot guarantee theoretical security against quantum computer and still requires time to mature and standardized. Second, quantum-key distribution (QKD) which relies on the quantum physics, is theoretically safe while its usage is limited to fiber-based scenarios currently and requires quantum-physics-based hardware support. Third, symmetric key-based systems, e.g., Kerberos, 3GPP mobile networks, are already resistant to attack by quantum computer [1]. However, Kerberos-like systems faces problems when applied to wide-scale public network, including how to safely deliver initial keys to terminals and how to refresh the keys.

Indeed, QKD provides a practical quantum-safe solution to deliver large number of keys from key distribution center (KDC) to terminals instead of using couriers, which can supplement the symmetric key management systems. The solution we would like to demonstrate is to construct a service-oriented QKD network which combine the advantages of QKD, KDC and PQC, in order to provide quantum-safe key management service. It is deemed to be able to achieve a real-world quantum-safe internet today and can greatly expand the usage of QKD.

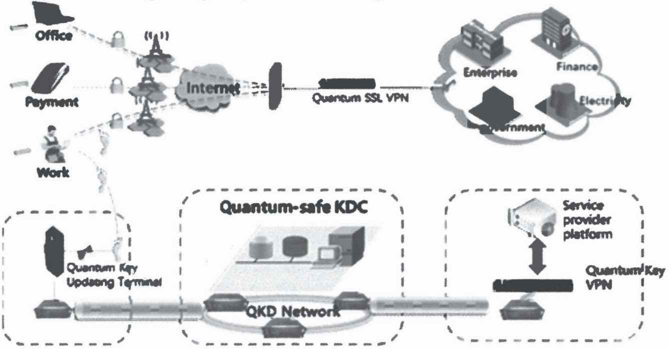

Fig. 1 QKD and KDC combined quantum-safe internet solution

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Inside the editorial process at *Nature Communications*

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Nature Communications is an open access journal that publishes high-quality research from all areas of the natural sciences. Papers published by the journal represent important advances of significance to specialists within each field. In this talk I will provide an editor's-eye-view into the publishing process at *Nature Communications*. I will discuss details of the editorial and peer-review processes across the life of a manuscript from submission to acceptance, describe initiatives to maintain transparency in peer-review and publication, and mention some key aspects to consider as an author when submitting to the *Nature* family of journals.

Simultaneous, full characterization of a single-photon state

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As single-photon sources become more mature and are used more often in quantum networks and measurement applications, the details of their characterization become more important. Single-photon-like light is often characterized by the device's photon flux—its brightness, and two quantum properties: the suppression of multi-photon components and the photon indistinguishability. While it is desirable to obtain these quantities from a single measurement, currently two or more measurements are used.

Here we simultaneously determine the brightness, the suppression of multi-photon content, the indistinguishability, and the statistical distribution of number states to third order for a quantum light source [1]. We use the light emitted from a single InAs quantum dot resonant with a planar microcavity and pumped by a pulsed-laser side-coupled to the cavity. However, the measurement is not source specific. The measurement uses a pair of two-photon ($n = 2$) number-resolving detectors, here modeled using single-photon detectors. Using a Fisher-information analysis, we show that the new method extracts more information per experimental trial than a conventional measurement for most input states, and is particularly more efficient for statistical mixtures of photon states. Furthermore, $n \geq 3$ number-resolving detectors provide no additional advantage in the single-photon characterization. Thus, using this $n=2$, number- resolving detector scheme will provide new advantages in a variety of quantum optics measurements and system characterization.

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Organic molecules for quantum technologies: State of the art and future prospects

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Organic molecules of polyaromatic hydrocarbons were the first system in the solid state to show single photon emission [1,2]. However they are still considered unconventional sources of non-classical light. I will try to unveil part of the mystery behind such quantum emitters and show how they could effectively contribute to integrated quantum photonic platforms.

I will report on fluorescence coupling from a single molecule to a planar optical antenna [3] and a single-mode dielectric waveguide [4], discuss the integration of single quantum emitters into hybrid dielectric-plasmonic devices [5] and the coupling with 2D materials [6]. I will present our recent results about the fabrication of single-molecule doped nancrystals, preserving the optical properties of the bulk system, i.e. negligible blinking and spectral diffusion [7]. Eventually, I will report on ultrafast time-resolved transient spectroscopy on a single molecule [8].

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Nonlinear optics with hot Rydberg atoms

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The exceptional large polarizability of highly excited Rydberg states can be exploited in manifold ways in spectroscopy, quantum optics and many body quantum physics. Most experiments on interacting Rydberg atoms in the last decade have been carried out with ultracold gases. Especially the realization of non-classical light states with the help of ultracold Rydberg interactions has attracted attention. Here I want to present how Rydberg excitations in hot vapours confined in microscopic cells can also produce non-classical light fields.

Quantum Networks with Spins in Cavities

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Spins in solids can exhibit strong optical transitions and exceptional coherence properties. This makes them a promising system towards the realization of global quantum networks. Pioneering experiments have shown entanglement between two remote spins, associated with the Nitrogen-vacancy (NV) center in diamond, over a distance of 1.3km [1]. However, exploring the full potential of quantum networks requires to further increase the separation and number of entangled particles. In this respect, two major challenges have to be addressed. First, one has to overcome inevitable imperfections in the control of the spins via quantum error correction. I will present first results in this direction, namely the distillation of entanglement between remote spins [2].

The second challenge is that the efficiency of photonic quantum network links has to be increased by orders of magnitude. To this end, we are working towards a deterministic spin-photon interface that is implemented by embedding spins in micrometer-thin crystals into Fabry-Perot resonators [3]. This should enable an increase of the remote entanglement rate between Nitrogen-Vacancy spins by more than three orders of magnitude.

Further enhancement, in particular over long distances, would require to convert the emitted photons to the telecommunication frequency band where the absorption of glass fibers is minimal. A potential alternative is to use Erbium spins, which is the only known impurity with coherent optical transitions in this frequency regime. Recent experiments have shown Purcell enhanced emission [4]. However, the 14 ms long lifetime of the excited states of Erbium requires to strongly improve the cooperativity. I will present the current status of a new experiment that tries to achieve this via High-finesse Fabry-Perot resonators with mode volumes approaching a single cubic wavelength.

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Nano building blocks for quantum networks

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With the aim of realizing complex quantum networks, we develop quantum devices based on nanostructures to generate quantum states of light with semiconductor quantum dots, single photon detectors based on superconducting nanowires and on-chip circuits based on waveguides to filter and route light.

The generation of single photons can readily be performed with single quantum dots. We demonstrate a very high single photon purity exceeding 99.99% generated at 795 nm with GaAs quantum dots[1], these quantum emitters also allow for interfacing with atomic ensembles. To enable long distance communication, we are also developing devices based on single InAs quantum dots able to emit at telecom frequencies[2].

Quantum entanglement is an important resource for quantum technologies, we will demonstrate generation of entanglement with quantum dots and discuss the limits to fidelity with the biexciton-exciton cascade[3].

To allow for complex architectures, on-chip integration is desirable. We will demonstrate filtering and routing of single photons with tunable ring resonators on a chip and discuss the scalability of this approach[4].

Generation and manipulation of quantum states of light would be useless without single photon detectors. We are therefore developing high-performance single photon detectors based on superconducting nanowires and will present state-of-the-art performance in terms of detection efficiency and time resolution[5].

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