Quantum Control of Light

783. WE-Heraeus-Seminar

28 Mar - 31 Mar 2023
at the Physikzentrum Bad Honnef/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
The Foundation is Germany's most important private institution funding physics.

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Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 783. WE-Heraeus-Seminar:

Photons – the elementary quanta of light – are essentially devoid of interactions, which makes them ideal carriers of information. In fact, our ability to generate, control and detect light has not only revolutionized modern telecommunication, but has had a broad impact on science and society, from remote sensing in meteorology and climatology, over optical tomography in biomedicine to the recent detection of gravitational waves. Yet, the possibility to exploit quantum mechanical phenomena for such tasks is opening up entirely new horizons. Indeed, quantum effects, such as coherence, quantum superposition and quantum entanglement constitute the underlying principles for future optical technologies that may, for example, enable quantum-enhanced imaging, fundamentally secure communication and quantum computing. All of this requires the ***quantum control of light***, i.e. the ability to generate and manipulate light at the level of single photons. With the inherent lack of photon interactions, this ultimate form of optical control has remained a grand challenge and constitutes the ambitious goal of the novel research field of quantum nonlinear optics.

Here, interaction of single photons with matter and saturation of individual quantum emitters is combined to realize nonlinear optical media which response depends on the exact number of photons inside the medium. The resulting few-photon nonlinearity is equivalent to an effective interaction between individual photons, which can be exploited to realize photonic quantum technology building blocks as well as highly controllable few- and many-body systems of strongly correlated photons.

This seminar, which will bring together about 80 participants in March 2023, will provide a comprehensive overview of the different platforms and approaches of this rapidly developing field. Leading international experts review the present status of the control of light photon by photon and the prospects of strongly correlated quantum many-body states of photons, from both the experimental and theoretical point of view. The workshop in particular aims to highlight future trends and perspectives. Participants are invited to present their current research in the poster sessions. In addition, outstanding contributions are selected for contributed talks.

Scientific Organizers:

Prof. Dr. Sebastian Hofferberth	Universität Bonn, Germany E-mail: hofferberth@iap.uni-bonn.de
Prof. Dr. Klaus Mølmer	Niels Bohr Institute, Copenhagen, Denmark E-mail: klaus.molmer@nbi.ku.dk
Prof. Dr. Thomas Pohl	Aarhus University, Denmark E-mail: pohl@phys.au.dk

Introduction

Administrative Organization:

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Martina Albert

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Registration:

Martina Albert (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Tuesday (16:00 h – 20:00 h)
and Wednesday (08:00 – 12:30 h)

Program

Program

Tuesday, 28 March 2023

16:00 – 20:00	**Registration**	
From 18:00	*BUFFET SUPPER*	
19:30 – 19:45	Scientific organizers	**Welcome / Introduction**
19:45 – 20:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
Open end	**Discussion**	

Wednesday, 29 March 2023

08:00	*BREAKFAST*	
09:00 – 09:40	Jaqueline Bloch	**Kardar Parisi Zhang Universal Scaling in the Coherent Emission of Polariton Condensates**
09:40 – 10:20	Janne Ruostekoski	**Interaction of Light with Planar Atomic Arrays**
10:20 – 11:00	Jonathan Simon	**Making & Probing Photon Fluids and Solids**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	**Poster Flash 1**	
12:30 – 12:40	Conference photo	
12:40	*LUNCH*	

Program

Wednesday, 29 March 2023

14:00 – 14:40	Susanne Yelin	**Cooperative Arrays: A novel Quantum Tool**
14:40 – 15:20	Charles S. Adams	**Seeing the invisible: Rydberg Atoms as an Interface to the Optical**
15:20 – 16:00	Anders S. Sørensen	**Strongly Interacting Photons based on two-level Systems coupled to Waveguides: one, two, many**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:10	Stephan Dürr	**A Qantum-Logic Gate between two Optical Photons with an Average Efficiency above 40%**
17:10 – 17:50	Darrick Chang	**The Ultimate Limits to Refractive Index: From Quantum Optics to Quantum Chemistry**
17:50 – 18:30	Ofer Firstenberg	**Quantum Vortices of Strongly Interacting Photons**
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*	
19:30 – 20:10	Christine Silberhorn	**Controlling the Temporal Modes of Pulsed Quantum Light**
Open end	**Poster Session 1 / Discussion**	

Program

Thursday, 30 March 2023

08:00	*BREAKFAST*	
09:00 – 09:40	Jeff Thompson	**Indistinguishable Single Photons from a Single Er3+ ion**
09:40 – 10:20	Ana Maria Rey	**Emergent Entangled Dark States from Superradiance Emission in Multi-Level Atoms**
10:20 – 11:00	Robin Kaiser	**Resonant Dipole-Dipole Interactions: Dicke Subradiance and Anderson Localisation**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	**Poster Flash 2**	
12:30	*LUNCH*	
14:00 – 14:30	Doerte Blume	**Photon-Induced Droplet-like Bound States in One-Dimensional Qubit Array**
14:30 – 15:00	Sophie Hermans	**Entangling Remote Qubits using the Single-Photon Protocol: An in-depth Theoretical and Experimental Study**
15:00 – 15:30	Alexei Ourjoumtsev	**Quantum Engineering of Light with an Intracavity Rydberg Superatom**
15:30 – 16:00	Wenchao Xu	**Repulsive Photons in a Quantum Nonlinear Medium**
16:00 – 18:30	**Excursion Drachenfels**	
18:30	*DINNER*	
19:30 – 20:10	Arno Rauschenbeutel	**Observation of Superradiant Bursts in Waveguide Quantum Electrodynamics**
Open end	**Poster Session 2 / Discussion**	

Program

Friday, 31 March 2023

08:00	*BREAKFAST*	
09:00 – 09:40	Julian Leonard	**From Quantum Gas Microscopy to Photon-Mediated Interactions**
09:40 – 10:20	Beatrix Olmos-Sanchez	**Dispersionless Subradiant Photon Storage in one-dimensional Emitter Chains**
10:20 – 11:00	Antoine Browaeys	**Collective Light Scattering in Cold Atomic Ensembles: Super-Radiance & Driven Dicke Model**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 12:00	Alexander Poddubny	**Subradiant States in Waveguide Quantum Electrodynamics**
12:00 – 12:40	Nina Stiesdal	**Waveguide QED with Rydberg Superatoms**
12:40 – 12:50	Scientific Organizers	**Closing remarks and poster awards**
12:50	*LUNCH*	

End of seminar and departure

NO DINNER for participants leaving on Saturday!

Abstracts of Lectures

(in alphabetical order)

Seeing the invisible: Rydberg atoms as an interface to the optical

C. S. Adams[1]

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Durham University, Durham DH1 3LE, UK.

Laser-excited atoms, such as Rydberg atoms, have strong resonances at frequencies spanning six orders of magnitude in the electromagnetic spectrum from radio to terahertz to optical. The ability to couple these resonances together means that atoms can be employed as remarkable versatile sensors with a direct optical read-out. We might want to sense a field that is otherwise difficult to detect such as terahertz field [1] or a particle that does not couple strongly to the optical.

In this talk, I will focus on different aspects of Rydberg quantum technology [2] from single-photon read-out of a microwave field [3] to sensing a polar molecule [4].

References

[1] L. Downes *et al*. Phys. Rev. X **10**, 011027 (2020).
[2] C. S. Adams *et al*. J. Phys. B. **53**, 012002 (2019).
[3] N. L. R. Spong *et al*. Phys. Rev. Lett. **127**, 063604 (2021)
[4] D. R. Rutley *et al*. in preparation

Kardar Parisi Zhang universal scaling in the coherent emission of polariton condensates

Jacqueline Bloch

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The Kardar–Parisi–Zhang (KPZ) equation[1], originally derived to describe the kinetic roughening of growing interfaces is a stochastic non-linear differential equation that applies to a large class of non-equilibrium systems, ranging from the growth of nematic liquid crystal clusters, of bacterial colonie, or the propagation of a combustion front. The shape of such an interface $h(\mathbf{r},t)$ is described by the following stochastic equation:

$$\partial_t h = \nu \nabla^2 h + \frac{\lambda}{2}(\nabla h)^2 + \eta,$$

where the first term is a smoothening diffusion, the second term is a crucial nonlinear contribution that leads to critical roughening of the interface and η is a Gaussian noise. Interestingly the spatial and temporal correlation functions of $h(\mathbf{r},t)$ show power law decays, with universal critical exponents that only depend on the dimensionality of the system.

Recently, it was discovered that, under certain assumptions, the phase dynamics of a polariton condensate also obeys the celebrated KPZ equation [2-4]. Since the phase is a compact variable, periodically defined between 0 and 2π, the physics is enriched by the possible emergence of vortices. Actually even in 1D, where usually vortices are excluded, exotic spatio-temporel vortices have been predicted to play a role [5].

In the present talk, after a general introduction to the system, I will explain how we could generate extended 1D polariton condensates [6] and probe their first order coherence. We demonstrate that the decay of the first order coherence in space and time present universal scaling laws characteristic for the KPZ universality class in 1D [7]. We reproduce these results by solving numerically the Gross Pitaevskii equation for many different realizations of the noise. We further explore the condensate physics, by analyzing the phase fluctuations in the numerical simulations. We evidence the nucleation of sparse spatio-temporal vortices, which appear in pairs of opposite helicity. These vortex pairs are responsible for abrupt 2π phase jumps, separated by plateaus where KPZ correlations develop. These results evidence that KPZ correlations are robust against these topological defects as long as their density is not too large.

Our work highlight the profound difference between driven-dissipative out of equilibrium condensates and their equilibrium counterparts. We anticipate that this physics should also be relevant in extended vertical cavity lasers.

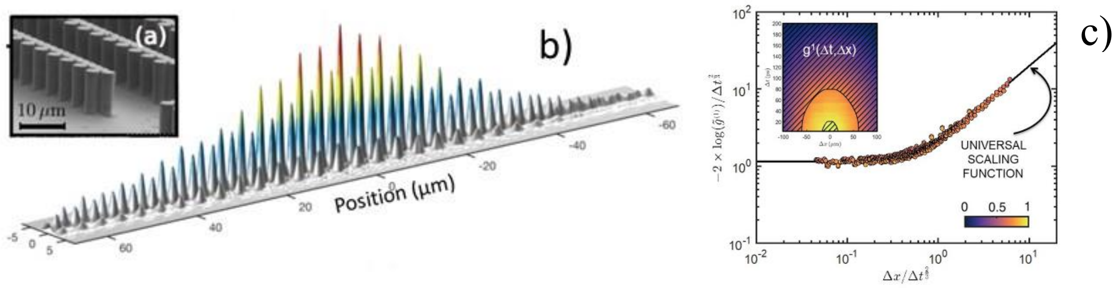

Fig. 1 a) Scanning electron microscopy image of a 1D polariton lattice; b) Three dimensional representation of a polariton condensate intensity (linear vertical scale) along a 1D polariton lattice such as the one shown in a; c) First order coherence data points ploted in rescaled units (symbols); the solid black line is the universal KPZ scaling function. Inset: measured first order coherence as a function of time and space. The points of the main figure are taken in the orange region.

References

1. M. Kardar, G. Parisi, and Y. C. Zhang, Dynamic Scaling of Growing Interfaces, Phys. Rev. Lett. 56, 889 (1986)
2. E. Altman, et al., Two-Dimensional Superfluidity of Exciton Polaritons Requires Strong Anisotropy, Phys. Rev. X 5, 011017 (2015).
3. K. Ji, et al., Temporal coherence of one-dimensional nonequilibrium quantum fluids, Phys. Rev. B 91, 045301 (2015).
4. L. He, et al., Scaling properties of one-dimensional driven-dissipative condensates, Phys. Rev. B 92, 155307 (2015)
5. L. He et al, Space-time vortex driven crossover and vortex turbulence phase transition in one-dimensional driven open condensates. Physical review letters 118, 085301 (2017).
6. F. Baboux, et al., Unstable and stable regimes of polariton condensation, Optica 5, 1163 (2018)
7. Q. Fontaine et al, Kardar-Parisi-Zhang universality in a one-dimensional polariton condensate, Nature 608, 687 (2022)

Photon-induced droplet-like bound states in one-dimensional qubit array

J. Talukdar[1] and D. Blume[1]

[1]*Homer L. Dodge Department of Physics and Astronomy and CQRT, The University of Oklahoma, 440 W. Brooks St., Norman, Oklahoma 73019, USA*

We consider an array of N_e non-interacting qubits or emitters that are coupled to a one-dimensional cavity array with tunneling energy J and non-linearity of strength U. The number of cavities is assumed to be larger than the number of qubits. Working in the two-excitation manifold, we focus on the bandgap regime where the energy of two excited qubits is off-resonant with the two-photon bound state band. A two-step adiabatic elimination of the photonic degrees of freedom gives rise to a one-dimensional spin Hamiltonian with effective interactions; specifically, the Hamiltonian features constrained single-qubit hopping and pair hopping interactions not only between nearest neighbors but also between next-to-nearest and next-to-next-to-nearest spins. For a regularly arranged qubit array, we identify parameter combinations for which the system supports novel droplet-like bound states whose characteristics depend critically on the pair hopping. The droplet-like states can be probed dynamically. The bound states identified in our work for off-resonance conditions are distinct from localized hybridized states that emerge for on-resonance conditions.

Collective light scattering in cold atomic ensembles: super-radiance & driven Dicke model

Antoine Browaeys

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This talk will present our recent work on the observation of super-radiance in a cloud of cold atoms and the implementation of the driven Dicke model in free space [1]. We start from an elongated cloud of laser cooled atoms that we excite either perpendicularly or along its main axis. This situation bears some similarities with cavity quantum electrodynamics: here the cavity mode is replaced by the diffraction mode of the elongated cloud. We observe superradiant pulses of light after population inversion. When exciting the cloud along the main axis, we observe the Dicke super-radiant phase transition predicted 40 years ago and never observed in free space. We also measure the statistics of the emitted light and find that it has the properties predicted for a super-radiant laser.

Reference

[1] Giovanni Ferioli, Antoine Glicenstein, Igor Ferrier-Barbut, Antoine Browaeys, "Observation of a non-equilibrium superradiant phase transition in free space", arXiv:2207.10361

The ultimate limits to refractive index: from quantum optics to quantum chemistry

Darrick Chang

ICFO, Theoretical Quantum Nanophotonics, Castelldefels, Spain

It is interesting to observe that all known materials have an index of refraction that is of order unity at visible wavelengths. This is quite different than any other material property (such as density, conductivity, specific heat), which can vary by orders of magnitude, and depends on the system being a gas vs. solid, insulating vs. conducting, etc. Strangely, there is no deep underlying theory of why refractive index has this seemingly universal property. This is despite the immense technological importance that an ultrahigh index material would have, as the index describes how much the wavelength of light can be reduced, and thus directly determines the Minimum footprint of optical devices.

Separately, it is well-known within quantum optics that a single, isolated atom can have an extraordinarily strong response to near-resonant light, as characterized by a scattering cross section that is much larger than its physical size. Substituting this known result into standard electrodynamics formulas for material refractive index results in a predicted index of 10^5 at the densities of a solid. Here, we will discuss why these textbook formulas break down, and our ongoing efforts to develop a more fundamental theory of refractive index and its limits. Our theory suggests that the low refractive index observed in everyday life is not necessarily fundamental, and a low-loss, ultrahigh-index material of n~30 might be possible. This theory combines ideas from quantum optics, quantum chemistry, and non-perturbative multiple scattering of light, which suggests why an answer to the refractive index problem might have been elusive in the past.

A quantum-logic gate between two optical photons with an average efficiency above 40%

Thomas Stolz, Hendrik Hegels, Maximilian Winter, Bianca Röhr, Ya-Fen Hsiao, Lukas Husel, Gerhard Rempe, and Stephan Dürr

Max-Planck Institute of Quantum Optics, Garching, Germany

Optical qubits uniquely combine information transfer in optical fibers with a good processing capability and are therefore attractive tools for quantum technologies. A large challenge, however, is to overcome the low efficiency of two-qubit logic gates. The experimentally achieved efficiency in an optical controlled NOT (CNOT) gate reached approximately 11% in 2003 and has seen no increase since. Here, we report on a new platform that was designed to surpass this long-standing record. The new scheme avoids inherently probabilistic protocols and, instead, combines aspects of two established quantum nonlinear systems: atom-cavity systems and Rydberg electromagnetically induced transparency. We demonstrate a CNOT gate between two optical photons with an average efficiency of 41.7(5)% at a postselected process fidelity of 81(2)% [1]. Moreover, we extend the scheme to a CNOT gate with multiple target qubits and produce entangled states of presently up to 5 photons. All these achievements are promising and have the potential to advance optical quantum information processing in which almost all advanced protocols would profit from high-efficiency logic gates.

References

[1] T. Stolz et al. Physical Review X **12**, 021035 (2022).

Quantum vortices of strongly interacting photons

O. Firstenberg

Weizmann Institute of Science

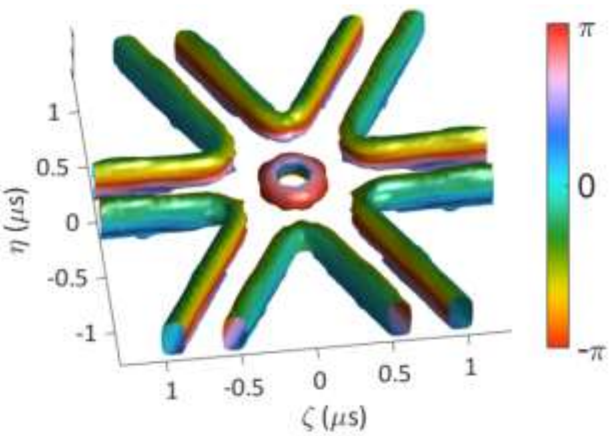
Have you ever tried dragging a plate through the surface of a water pool?

https://www.youtube.com/watch?v=pnbJEg9r1o8

Quite excitingly, you would form a pair of vortex and antivortex, which would propagate steadily on the water's surface!

In optics, vortices manifest as phase twists of the electromagnetic field, usually formed by the interaction with matter. Vortex formation due to light interacting with light requires strong optical nonlinearity and has therefore been confined, until now, to the classical regime. Recently, we have reached a new extreme regime of photon-photon interactions, in which quantum vortices – phase dislocations in the few-body wavefunction – are formed.

We will discuss the experimental realization of this effective photon-photon interaction in a quantum nonlinear medium based on ultracold Rydberg atoms. This interaction results in a faster phase accumulation for copropagating photon pairs. Similarly to a plate pushing water, the accumulation of localized excess phase produces a quantum vortex-antivortex pair within the two-photon wavefunction. The "conditional" π phase localized between these vortices can be used for deterministic quantum logic operations. Moreover, triplets of photons produce vortex lines and a vortex ring, giving rise to a 2π conditional phase. The deviation from the 3π conditional phase, expected for a quantum Kerr-nonlinear medium, attests to genuine three-photon interaction.



Entangling remote qubits using the single-photon protocol: an in-depth theoretical and experimental study

S. L. N. Hermans[1,2], M. Pompili[1], L. Dos Santos Martins[1], A. R.-P. Montblanch[1], H. K. C. Beukers[1], S. Baier[1], J. Borregaard[1] and R. Hanson[1]

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[2] Present address: Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA, United States of America.

Entanglement between different nodes will be an essential element of future quantum networks and will serve as a key ingredient for many of its applications, such as secure communication, distributed quantum computation and advanced quantum network protocols. The single photon protocol based on emitted photons encoded in number states [1,2], is especially suited to establish entanglement between distant stationary qubits with high generation rates in the presence of significant photon loss.

Here we present a detailed theoretical and experimental investigation of the single photon protocol and its various sources of infidelity. We have developed an extensive theoretical model and subsequently tailored it to our experimental setting, based on nitrogen-vacancy centers in diamond. Experimentally, we have verified the model by generating remote states for varying phase and amplitudes of the initial qubit superposition states and varying optical phase difference of the photons arriving at the beam splitter. We show the impact of a static frequency offset between the emitters and the effect of double optical excitation. Finally, we find that imperfect optical excitation can lead to a detection-arm-dependent entangled state fidelity and rate.

This work contributes to a better understanding of the effect of general experimental imperfections and its platform-independent insights can be used to improve entanglement generation on various systems, such as other solid-state defects and quantum dots.

References

[1] C. Cabrillo et al., Phys. Rev. A, **59 2**,, 1025–1033, (1999)
[2] S. Bose et al., Phys. Rev. Lett., **83 24**, 5158–5161, (1999)
[3] S. L. N. Hermans et al., New J. Phys. **25** 013011 (2023)

Resonant dipole-dipole interactions: Dicke subradiance and Anderson localisation

R. Kaiser

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The quest for Anderson localization of light is at the center of many experimental and theoretical activities. Cold atoms have emerged as interesting quantum system to study coherent transport properties of light. Initial experiments have established that dilute samples with large optical thickness allow studying weak localization of light [1], which has been well described by a mesoscopic model [2]. Recent experiments on light scattering with cold atoms have shown that Dicke super- or subradiance occurs in the same samples [3,4], a feature not captured by the traditional mesoscopic models. The use of a long range microscopic coupled dipole model [5] allows to capture both the mesoscopic features of light scattering and Dicke super- and subradiance in the single photon limit.
I will review experimental and theoretical state of the art on the possibility of Anderson localization of light by cold atoms.

References

[1] G. Labeyrie, F. de Tomasi, J.-C. Bernard, C.A. Müller, Ch. Miniatura, R. Kaiser, Phys. Rev. Lett., **83**, 5266 (1999)
[2] T. Jonckheere, C.A. Müller, R. Kaiser, Ch. Miniatura, D. Delande, Phys. Rev. Lett. **85**, 4269 (2000);
[3] W. Guerin, M.O. Araujo, R. Kaiser, Phys. Rev. Lett. **116**, 083601 (2016);
[4] M. O. Araujo, I. Kresic, R. Kaiser, W. Guerin, Phys. Rev. Lett. **117**, 073002 (2016);
[5] T. Bienaime, N. Piovella, R. Kaiser, Phys. Rev. Lett, **108**,123602 (2012)

From quantum gas microscopy to photon-mediated interactions

Julian Léonard

TU Wien, Vienna, Austria

Quantum simulations offer the unique opportunity to experimentally address outstanding problems in many-body quantum physics. Quantum gas microscopy brings this effort to the ultimate level of single particle control. I will present our recent results on the realization of a fractional quantum Hall state in an optical lattice, which we prepare through adiabatic quantum state engineering within the interacting Harper Hofstadter model. Our work provides a starting point for exploring other entangled topological matter with ultracold atoms.

Building upon those microscopy techniques, we are currently working on engineering photon-mediated interactions among individually controlled atoms. I will present our progress to build a novel platform with atoms coupled to the field of a high-finesse optical resonator. Such a system will enable partial non-destructive readout and the generation of multi-particle entanglement, and it offers a path to an efficient atom-photon interface for quantum communication applications.

Dispersionless subradiant photon storage in one-dimensional emitter chains

Marcel Cech[1] , Igor Lesanovsky[1,2] and Beatriz Olmos[1,2]

[1] *Institut für Theoretische Physik, Universität Tübingen, Tübingen, Germany*
[2] *School of Physics and Astronomy, The University of Nottingham, Nottingham, United Kingdom*

We provide the exact conditions for an optimal absorption, long-lived and dispersionless storage, and release, of a single photon in a sub-wavelength one-dimensional lattice of two-level emitters. We do so by exploiting the collective properties of the emitters' dynamics that arise by being coupled to the free radiation field. In particular, we detail two storage schemes. The first is based on the uncovering of approximate flat bands in the single-photon spectrum, such that a single photon can be stored as a wave packet with effective zero group velocity. For the second scheme we exploit the angular dependence of the interactions induced between the emitters and mediated via exchange of virtual photons, which on a ring gives rise to an effective trapping potential for the photon. In both cases, we are able to find, within current experimentally accessible parameters, photon storage fidelities close to one for times hundreds of times longer than the lifetime of a single atom.

Quantum engineering of light with an intracavity Rydberg superatom

V. Magro, J. Vaneecloo, S. Garcia and A. Ourjoumtsev

*JEIP, UAR 3573 CNRS, Collège de France, PSL University,
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Engineering quantum states of free-propagating light is of paramount importance for quantum technologies. Coherent states ubiquitous in classical and quantum communications, squeezed states used in quantum sensing, and even highly-entangled cluster states studied in the context of quantum computing can be produced deterministically, but they obey quasi-classical optical field statistics described by Gaussian, positive Wigner functions. Fully harnessing the potential of many quantum-engineering protocols requires using Wigner-negative states, so far produced using intrinsically probabilistic methods. I will describe the first fully deterministic preparation of Wigner-negative free-propagating states of light, obtained by mapping the internal state of an intracavity Rydberg superatom onto an optical qubit encoded as a superposition of 0 and 1 photons [1]. This approach allows us to reach a 60% photon generation efficiency in a well-controlled spatio-temporal mode, while maintaining a strong photon antibunching. By changing the qubit rotation angle, we observe an evolution from quadrature squeezing to Wigner negativity. Our experiment sets this new technique as a viable method to deterministically generate highly non-classical photonic resources, lifting several major roadblocks in optical quantum engineering.

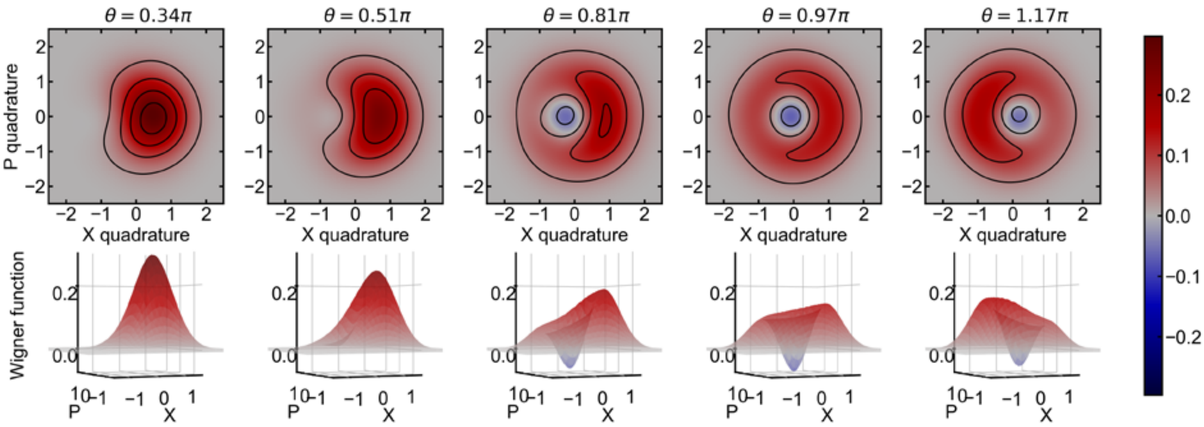

Figure 1: Experimentally reconstructed Wigner functions of photonic qubits cos(θ/2)|0⟩+ sin(θ/2)|1⟩ deterministically emitted by an intracavity Rydberg superatom.

References

[1] V. Magro, J. Vaneecloo, S. Garcia and A. Ourjoumtsev, arXiv:2209.02047

Subradiant states in waveguide quantum electrodynamics

Alexander Poddubny

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Waveguide quantum electrodynamics (WQED) is a rapidly developing field of quantum optics that studies interaction of propagating photons with localized quantum emitters, such as atoms, superconducting qubits and quantum dots [1]. The emergence of novel experimental platforms with highly coherent and ordered atomic emitter arrays has stimulated a new wave of interest to the classical problem of quantum optics: enhancement and suppression of spontaneous emission via constructive and destructive interference of photons from different emitters. Subradiant states, that form because of such destructive interference, provide important insights in the collective light-matter interactions and also promise applications for storage and processing of quantum light.

In this talk I will try to review recent theoretical and experimental progress in the studies of subradiant states in the waveguide setup. I will start with the basic concepts of wave interference, that enable explanation of formation of subradiant states in the single-photon regime. Next, I will discuss multiple-excited subradiant states [2] and subradiant states in the strongly driven systems [3]. I will demonstrate that the dependence of the lifetime of the correlations on the driving strength and the array period can be strongly nonmonotonous and is rather sensitive to the details of many-body interactions in the array.

References

[1] A.S. Sheremet, M.I. Petrov, I.V. Iorsh, A.V. Poshakinskiy, A.N. Poddubny, Rev. Mod. Phys. (2023, in press), arXiv:2103.06824

[2] A.V. Poshakinskiy and A.N. Poddubny, Phys. Rev. Lett. **127**, 173601 (2021)

[3] A.N. Poddubny, Phys. Rev. A **106**, L031702 (2022).

Observation of superradiant bursts in waveguide quantum electrodynamics

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Dicke superradiance describes the collective decay dynamics of a fully inverted ensemble of two-level atoms. There, the atoms emit light in the form of a short, intense burst due to a spontaneous synchronization of the atomic dipoles. In order to observe this phenomenon with an atomic ensemble in free space, the mean distance between adjacent atoms must be smaller than the emission wavelength. In contrast, here we experimentally observe superradiant burst dynamics with a one-dimensional ensemble of atoms where this distance exceeds the emission wavelength. This is enabled by coupling the atoms to a nanophotonic waveguide, which mediates long-range dipole-dipole interactions between the emitters. We excite the atoms by a resonant, fiber-guided probe pulse that is much shorter than the excited state lifetime. We realize strong inversion, with about 80% of the atoms being excited, and study their subsequent radiative decay into the guided modes [1]. The burst occurs above a threshold atom number, and its peak power scales faster with the number of atoms than in the case of standard Dicke superradiance. Moreover, we study the coherence properties of the burst and observe a sharp transition between two regimes: in the first, the phase coherence between the atoms is seeded by the excitation laser. In the second, it is seeded by vacuum fluctuations [2]. Our results shed light on the collective radiative dynamics of spatially extended ensembles of quantum emitters and may turn out useful for generating multi-photon Fock states as a resource for quantum technologies.

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Emergent entangled dark states from superradiance emission in multi-level atoms

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Subradiant states that emit light slower than independent atoms because of quantum interference have attracted widespread interest owing to their potential applications in quantum technologies. A long-standing challenge is finding simple ways to prepare a target many-body subradiant state that is also highly entangled. Optical cavities are natural candidates for creating highly entangled states since they have demonstrated the capability to create collective quantum many-body states with scalable entanglement. However, in generic atom-cavity experiments with two-level atoms, collective (i.e., fully symmetric) states are typically not dark but superradiant. In this talk I will discuss our proposal to use multilevel atoms coupled to a cavity to create dark states with scalable squeezing. I will discuss two cases, one where the atoms acquire scalable squeezing directly in a dark state, and one where squeezing is acquired in a bright state due to a combination of superradiance and coherent driving. In both cases, the multilevel structure allows at least two spin quadratures to be squeezed. Our findings are readily testable using alkaline-earth-like atoms trapped in optical cavities. These atoms are particularly well suited because of their pristine atomic multilevel structure, which contains a unique ground state manifold, and their ultra-narrow atomic transitions. The latter, combined with the fact that squeezed states in a dark excited manifold carry optical coherences, make this protocol a potential pathway for quantum-enhanced sensing of optical phases in atomic clocks.

Interaction of light with planar atomic arrays

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Resonant light can couple strongly to subwavelength-spaced planar arrays of atoms where multiple scattering mediates long-range interactions and cooperative atom response. The cooperative response can be harnessed for engineering collective radiative excitations that correspond to those formed by arrays of magnetic dipoles and other multipoles, even when the atoms only exhibit electric dipole transitions. Such optically active magnetism in neutral atomic system can be utilized in optical manipulation reminiscent of that considered in artificially fabricated metasurfaces. In particular, the atoms can form a Huygens' surface, a physical realization of the Huygens' principle, that provides an extreme wavefront control of transmitted light. We compare the response of atom arrays to that of cavity qed and also show how the cooperative many-body response can be described by notably simpler superatom models that accurately predict reflection, transmission, photon storage, and non-classical resonance fluorescence.

Controlling the temporal modes of pulsed quantum light

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Pulsed quantum states of light are an attractive resource for quantum communication and optical quantum measurements. The temporal-spectral degree of freedom offers distinct advantages for light-based quantum technologies. Temporal modes (TM) of quantum light pulses can be defined as field-orthogonal wave packet states, which are specified by their envelope functions and typically span a high dimensional system. They constitute a fiber-compatible high dimensional basis, because they occupy a single spatial mode.

Here, we demonstrate the control of the TM structure of quantum light by using non-linear processes for state preparation as well as for state manipulation and detection. We use highly efficient devices based on non-linear waveguide structures for the preparation and manipulation of TMs by means of engineered PDC and our quantum pulse gate (QPG) setups.

For pulsed parametric downconversion processes much effort has been devoted in recent years to engineer sources with uncorrelated spectra, which emit single TM pulsed photon pairs with no intrinsic structure and can achieve very high efficiencies. Contrariwise, we can explore the generation of multi-mode temporal states for multi-dimensional quantum information encoding.

We show that we can detect and analyse the TM structure of pulsed quantum light by using dispersion engineered sum frequency generation, this means QPG setups with subsequent single photon detection. Applying QPGs for quantum metrology, we can observe ultimate quantum timing resolution. For quantum communication a multi-output QPG provides the basis for future systems with efficient high-dimensional quantum information encoding.

Making & Probing Photon Fluids and Solids

J. Simon

Stanford University, Stanford CA, USA

In this talk, I will describe recent developments in the Simon/Schuster collaboration, where we are harnessing cavity quantum electrodynamics for both manybody physics and quantum information. I will begin with an overview of photonic quantum materials efforts [1], highlighting the analogy between photons in a lattice of cavities (or family of cavity modes [2]) and electrons in solids. I will then focus in on our explorations of Hubbard physics in a quantum circuit, where we have demonstrated the ability to build crystals of light using reservoir engineering [3], and more recently, disorder-assisted adiabatic approaches to preparation of fluids [4] and even cat states of fluids. Finally I will change gears and talk briefly about interfacing superconducting and optical cavities using Rydberg atoms, where we recently demonstrated a quantum limited mmwave-to-optical transducer with >50% transduction efficiency, 100's of kHz of bandwidth, and less than one noise photon [5].

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Strongly interacting photons based on two-level systems coupled to waveguides: one, two, many

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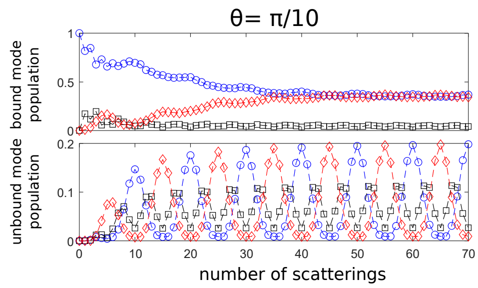
Photons rarely interact in free space, but by coupling them to quantum emitters it is possible to engineer strong effective photon interactions. The conceptually simplest system to realize such interactions is two-level systems strongly coupled to a waveguide. Since a single two-level atom can only absorb one photon, the transmission and reflection dynamics of a photon is strongly affected by the presence of another photon, and this induces an effective interaction among the photons. Despite its simplicity this system exhibits rich and interesting physics. I will discuss some of the effects that can be observed with it.

A particularly interesting effect is two-photon bound states [1]. These are the quantum limit of optical solitons [2]. I will discuss the physics of these bound states and how to observe unambiguous signatures of them. The clearest signature can be found for bound states in tunnel coupled waveguides. In this case unbound photons can freely jump between waveguides whereas photons in a bound state always jump simultaneously and at a much slower rate (see figure) [3].



Simulation of two-photon dynamics in tunnel coupled waveguides. Unbound photons (lower plot) oscillate between having two photons in one or the other waveguide (blue/red curves) by going through an intermediate state with one photon in each waveguide (black curves). In contrast photons in the bound state (upper plot) stick together and never have one photon in each waveguide.

For unbound photons the scattering dynamics exhibit a rich and complicated structure including inelastic scattering and scattering resonances. I will present a complete solution of the scattering dynamics [4]. This understanding of the scattering dynamics can be used as a starting point for an effective description of quantum many-body dynamics of multiple photons. As a particular example I will show that a photonic Tonks-Girardeau gas is a stable solution for a finite chain of weakly excited atoms in a waveguide.

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Waveguide QED with Rydberg superatoms

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The field of Waveguide QED investigates how light in a single mode propagates through a system of localized quantum emitters. Such an open system might at first sight appear simple, but can turn into an interesting quantum many-body system if the coupling between individual photons and individual emitters is sufficiently strong. In this case, the photons mediate an effective interaction between the distant emitters, and the cascaded interaction between photons and saturable emitters can be interpreted as a photon-photon interaction.

We experimentally realize effective two-level emitters coupled to a single quantized mode by exploiting the Rydberg blockade effect of atomic ensembles: N~10.000 atoms confined to a single blockaded volume only supports a single excitation and form a so-called Rydberg superatom. Due to the collective nature of the excitation gives rise to an enhanced coupling strength, and the superatom effectively represents a single emitter coupling strongly to single photons. The directional emission of the superatom into the initial probe mode realizes a waveguide-like system in free-space without any actual light-guiding elements [1].

This talk will discuss how we scale this system from one to few strongly coupled superatoms to study how the propagation of quantized light fields through a small emitter chain results in photon-photon correlations and entanglement between the emitters. We also show how the internal dynamics of the superatom is reflected in the transmitted field [2], and we discuss how controlled dephasing of the collective excitation into collective dark states can be used to subtract exact photon numbers from an incoming light pulse [3].

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Indistinguishable single photons from a single Er3+ ion

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Atomic defects in solid-state crystals are widely explored as single-photon sources and quantum memories for quantum communications networks based on quantum repeaters. Rare earth ions, in particular Er^{3+}, have several unique features including a telecom-band optical transition facilitating long-distance entanglement distribution, and compatibility with a broad range of materials and device structures. I will give an overview of recent work from our lab including fast photon emission from single Er^{3+} ions using silicon nanophotonic cavities [1], single-shot spin readout [2], sub-wavelength addressing based on spectral multiplexing [3] and coherent control of nearby nuclear spins [4]. Through systematic materials exploration, we have significantly extended the spin and optical coherence times of Er^{3+} ions, enabling indistinguishable single-photon emission [5]. I will conclude by discussing ongoing efforts to probe spin-spin interactions, and how these advances may be combined into a practical quantum repeater architecture.

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Repulsive photons in a quantum nonlinear medium

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Many promising applications of quantum technologies involve using photons, the smallest energy packets of light, as quantum information carriers. The ability to have a full control over photon-photon interactions opens up exciting directions, including building all-optical quantum devices, performing photonic quantum information processing, and studying novel many-body quantum states made with photons. Unfortunately, one drawback is that photons do not interact with each other in vacuum, which makes it challenging to manipulate a photon with another. In this talk, I will show by using a double-EIT scheme, an atomic ensemble can be used as a quantum nonlinear medium to facilitate and engineer photon-photon interactions at the single photon level. A full control over photon-photon interaction is achieved, with the interaction ranging from attraction to repulsion. These observations of repulsion between single photons and the ability to control the nature of interactions open a route to creating quantum matter composed of light such as a crystal of photons.

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Cooperative arrays: A novel quantum tool

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The physics of cooperative atoms/radiators in regular 2D arrays is dominated by two properties: first, a strongly frequency-selective reflectivity and second, the ability to confine polariton modes cleanly on the surface. This makes such a system highly sensitive to and controllable by light fields. Applications of such systems include quantum information processing, metrology, nonlinear single-photon techniques, and, with some extensions, geometry-dependent emergent spin-orbit coupling.

Posters

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Jessica Almeida	**Characterization of four-modes topological insulator by light matter interaction in Su-Schrieffer-Heeger chains**
Germaine Arend	**Towards generating photon Fock states using free electron beams**
Ivan Ashkarin	**Toffoli gate based on RF-induced Förster resonance in Rydberg atoms**
Mateus Biscassi	**From classical to quantum loss of light coherence**
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Alexander Bott	**Light-matter interaction with single-photon transitions for sensing beyond the Standard Model**
Hannes Busche	**Towards Rydberg quantum optics and hybrid quantum systems in a closed-cycle cryostat**
David Castells Graells	**Atomic waveguide QED with atomic dimers**
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Posters 1

Oliver Diekmann	**Ultrafast excitation exchange in a Maxwell-Fish-Eye lens**
Zahra Etesami	**Tunable negative lens based on gold nanorods**
Norman Vincenz Ewald	**Towards quantum memories in noble-gas nuclear spins with alkali metal vapour as optical interface**
Giovanni Ferioli	**Intensity correlations in the Driven Dicke Model**
Daniel Goncalves Romeu	**Local dissipation effects in the driven-dissipative Dicke phase transition**
Daniel Holleufer	**Oscillating phase transition in a chiral waveguide**
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Christian Kriso	**Two-photon excitation of exciton-polaritons for direct measurement of the polariton-polariton interaction strength**
Jan Kumlin	**Strongly Interacting Polaritons in Moiré Quantum Materials**
Kasper Jan Kusmierek	**Higher-order mean-field theory of chiral waveguide QED**

Valentin Magro	**Deterministic Free-Propagating Photonic Qubits with Negative Wigner Functions**
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Nicolas Fabre	**Time-frequency quantum metrology**
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Mateusz Mazelanik	**Quantum-memory-based time-frequency processor**
Christopher Mink	**Collective Radiative Interactions of Many-Particle Systems in the Discrete Truncated Wigner Approximation**
Baptiste Muraz	**Quantum simulation with circular states of strontium**
Krishna Nandipati	**Cavity Jahn-Teller Polaritons in Molecules**
Sile Nic Chormaic	**Multiphoton processes in atomic systems mediated by optical nanofibres**
Bartosz Niewelt	**Optical Fractional Fourier Transform in the time-frequency domain experimentally demonstrated via a quantum-memory setup**
Jan Nowosielski	**Theoretical analysis of mode-sorting techniques in the time-frequency domain**
Simon Panyella Pedersen	**Quantum nonlinear metasurfaces from dual arrays of ultracold atoms**

Posters 2

Michał Parniak	**Continuous-wave microwave-to-optical conversion beyond the blackbody radiation noise using room-temperature atoms**
Abhijit Pendse	**Vibrational energy transfer between trapped atoms via Rydberg Excitation**
Riccardo Pennetta	**Light-matter interaction at the transition between cavity and waveguide QED**
Hannes Pfeifer	**Polymer membrane resonators in fiber Fabry-Perot cavities**
Jonathan Pritchett	**Giant Cross Kerr Effect in Cuprous Oxide**
Siavash Qodratipour	**Towards time-bin entangled photon cluster states**
Lukas Rachbauer	**The Quantum Wigner-Smith Operator: Micromanipulation, Metrology and Vacuum Forces**
Juan Román-Roche	**Exact solution for quantum strong long-range models using a generalized Hubbard–Stratonovich transformation from cavity QED**
Philipp Schneeweiss	**Tailoring photon statistics with an atom-based two-photon interferometer**
Jim Skulte	**Dynamical phases in an atom-cavity system: From time crystals to dark states**
Philipp Stammer	**Quantum electrodynamics of intense laser-matter interactions: A tool for quantum state engineering**

Posters 2

William Staunton	**Distribution of Engineered Entangled States across a field installed Metropolitan Fiber Network**
Felix Tebbenjohanns	**Observation of superradiant bursts in waveguide QED**
Samuel White	**Quantum simulation with Rydberg states of erbium atoms**
Bennet Windt	**Fermionic matter-wave quantum optics with cold-atom impurity models**
Lida Zhang	**Chiral quantum-optical elements and waveguide-QED with sub-wavelength Rydberg-atom arrays**

Abstracts of Posters

(in alphabetical order)

Switching a subwavelength atomic array using a single Rydberg atom

Daniel Adler[1,2,3], Kritsana Srakaew[1,2], Pascal Weckesser[1,2], Simon Hollerith[1,2], David Wei[1,2], Immanuel Bloch[1,2,3], and Johannes Zeiher[1,2]

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Understanding and tuning light-matter interactions is essential for numerous applications in quantum science. The cooperative optical response between light-coupled atoms has recently led to the realization of a sub-radiant mirror formed by an atomic monolayer with strong light-matter coupling even down to the level of single photons [1].
Here, making use of the single-site resolution provided by our quantum gas microscope setup, we control the optical response of such an atomic mirror using a single ancilla atom excited to a Rydberg state [2]. The switching behavior is controlled by admixing Rydberg character to the atomic mirror and exploiting strong dipolar Rydberg interactions with the ancilla. Driving Rabi oscillations on the ancilla atom, we demonstrate coherent control over the degree of transmission and reflection. Finally, increasing the mirror size directly reveals the spatial area around the ancilla atom where the switching is effective.
Our results pave the way towards novel quantum metasurfaces, the creation of controlled atom-photon entanglement and deterministic engineering of quantum states of light.

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Characterization of four-modes topological insulator by light matter interaction in Su-Schrieffer-Heeger chains

M. L. Bera[1], Jessica O. de Almeida[1], M. Dziurawiec[2], M. Plodzien[1], M. Lewenstein[1,3], T. Grass[1,4], and U. Bhattacharya[1]

During the last decades the study of electronic behaviour in new materials attracted a lot of interest, due to the miniaturization of technology, and the discovery of quantum effects in this scale of micro and nano physics. In low-dimensional systems with open boundary conditions, the presence of edge electrons can reveal topological properties in the material, as for example the topological phases which define the nature of the material as insulator or metallic.

The techniques to characterize topological phases were developed based on nonlinear spectroscopy. For example, in solids, the exposure to strong laser fields, with a laser strength much larger then the binding energy of valance electron, results in a transmitted light in the non-perturbative or extremely nonlinear regime, producing high-harmonic generation (HHG). The simplest model to study topological properties and HHG generation in complex many-body condensed matter, is the 1D SSH model.

The HHG spectroscopy characterises the number of zero-energy modes or edge modes, therefore, the number of topological phases present in the system. Implementing the SSH model, allowing for only nearest neighbour hopping, it is possible to characterise two topological zero modes. Moreover, adding to this model model the allowance also for the next nearest neighbours interaction, shows the presence of four topological edge modes. Nevertheless, the difference in the HHG spectrum between two and four topological edge states is not obvious. In our work, we discuss how to distinguish between two and four topological edge modes based on the HHG spectrum.

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Towards generating photon Fock states using free electron beams

Germaine Arend[1,2], Armin Feist[1,2], Guanhao Huang[3], Yujia Yang[3], Jan-Wilke Henke[1,2], Arslan Sajid Raja[3], F. Jasmin Kappert[1,2], Jiahe Pan[3], Hugo Lourenco-Martins[1,2], Zheru Qiu[3], Junqiu Liu[3], Ofer Kfir[1,2], Tobias J. Kippenberg[3], Claus Ropers[1,2]

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The advancing field of quantum communication harnesses the quantum correlations of bipartite systems and has so far mainly relied on the generation of photon pairs as well as their interactions with different quantum systems. However, the interaction of single photons with free electrons, being powerful nanoscale probes, has not yet been considered. In particular, observing the weak coupling of single electrons and photons was inhibited by limited control over the optical states and the lack of coincidence detection capabilities.

In the presented work we combine integrated photonics with a transmission electron microscope (TEM) [1] to efficiently create and detect electron-photon pairs. The inelastic scattering of free electrons with the evanescent optical field of a fiber-coupled Si_3N_4 microring resonator placed into the TEM induces the generation of cavity photons as well as a quantized energy loss on the electron side. The detection and temporal correlation of both particles demonstrates a distinct peak of coincidence events for an electron energy loss of 0.8eV - the energy of the generated photon – highlighting their common origin [2]. Thus, post selecting events with specific energy loss or delay time allows direct access to the correlated pairs. Further conditioning on one detection channel could therefore establish single photon or single electron heralding.

In summary, we demonstrate the generation of free electron cavity photon pairs, combining two very different physical systems. This enables new experimental concepts in free-electron quantum optics, leading to electron-photon entanglement, as well as novel sources of photon Fock states.

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Toffoli gate based on RF-induced Förster resonance in Rydberg atoms

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Precise control of many-body Rydberg interactions in atomic registers is extremely relevant for quantum computing applications. In this regard, the use of RF and microwave radiation for the induction of interatomic transitions is of great interest nowadays. In this research, we investigated and numerically modeled RF-induced three-body Förster resonances of a fine-structure-changing type $\left|nP_{3/2}\right\rangle^{\otimes 3} \to \left|nS_{1/2};(n+1)S_{1/2};nP_{1/2}\right\rangle$. We also proposed a scheme for the application of such resonances to implement a multi-qubit quantum Toffoli gate. This scheme is a significant development of our previous proposal [1]. We show that the use of RF-induced resonances makes it possible to significantly simplify the quantum gate implementation process, and also gives new nodes for precise control of the atomic system, allowing to increase the quantum gate fidelity.

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From classical to quantum loss of light coherence

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Light is a precious tool to probe matter, as it captures microscopic and macroscopic information on the system. We here report on the transition from a thermal (classical) to a spontaneous emission (quantum) mechanism for the loss of light coherence from a macroscopic atomic cloud [1]. The coherence is probed by intensity-intensity correlation measurements realized on the light scattered by the atomic sample [2,3], and the transition is explored by tuning the balance between thermal coherence loss and spontaneous emission via the pump strength. Numerical simulations are realized in parallel with the experimental measurements , which allow to identify the critical role of the low temperature in the observation of the transition. Furthermore, the simultaneous measurement of the field-field correlations allows us to verify that the Siegert relation is valid for both regimes [4,5]. The Siegert relation establishes an equivalence between the (loss of) coherence for the field and for the intensity, thus, we can conclude that the field does not suffer extra loss of coherence compared to the intensity. Our results illustrate the potential of cold atom setups to investigate the classical-to-quantum transition in macroscopic systems.

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Beam Splitters and Mirrors with Aberrations in Matter-Wave Interferometry

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The control of light becomes increasingly important for quantum sensing as a means to venture past the standard quantum limit. Light-pulse atom interferometers have matured into capable sensors for small inertial and electromagnetic forces and are employed to test the foundations of physics. Today, most cold-atom based matter-wave interferometers use either single-photon[1] or two-photon[2,3] transitions in combination with large-momentum-transfer techniques. These schemes are susceptible to imperfections in the optical beams.

In our contribution, aberrations are assumed to be locally small perturbations of an external electromagnetic field which facilitates an analytical treatment to circumvent long computation times for numerical simulations[4]. We introduce an effective analytical model for diffraction including parasitic spatio-temporal effects during a light pulse. Such models can be derived from a general perturbative approach for two-level quantum systems with non-commutative elements in the quasi-resonant regime. In particular, we show how to reconstruct an approximate analytic solution by exploiting the oscillatory properties of the unperturbed solution. After comparison of this solution with the ideal case we are able to identify the effects of general perturbative optical potentials. Based on such a model, effective operators describing the evolution are derived.

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Light-matter interaction with single-photon transitions for sensing beyond the Standard Model

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Atom interferometers have been successfully employed for high-precision measurements of various quantities, for instance accelerations [1] as well as fundamental constants [2]. Differential measurements with atom interferometers are a promising avenue for demanding sensing applications such as the detection of gravitational waves [3] and light scalar dark matter [4]. Most current atom interferometers rely on two-photon transitions used for Raman or Bragg diffraction. Single-photon transitions driven by a single laser are a hopeful alternative for such differential detectors as they offer a natural mitigation of laser phase noise [5].
In our contribution we derive an effective atomic two-level model for both Raman and single-photon transitions, including perturbations from effects beyond the Standard Model; in particular we include violations of the Einstein equivalence principle and effects of light scalar dark matter. We obtain a description of the time-evolution of such effective atomic two-level systems during their interaction with light. Therefore, we determine phase contributions imprinted by the Standard Model violations on the atoms interacting with the lasers in an atom interferometer.

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Towards Rydberg quantum optics and hybrid quantum systems in a closed-cycle cryostat

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Strongly interacting Rydberg atoms are a popular platform not only for quantum computing and simulation, but also to study the interaction between individual photons and single quantum emitters in the form of collectively excited atomic ensembles which are limited to a single excitation due to Rydberg blockade. Applications of the resulting single-photon non-linearities include photon sources, optical transistors, or quantum gates. Rydberg atoms also offer electric dipole transitions over a wide range of the electromagnetic spectrum ranging from optical transitions close to the ground state to strong microwave transitions between neighbouring Rydberg states.

This makes Rydberg atoms an attractive ingredient for hybrid quantum systems that aim at interconnecting quanta in vastly different frequency regimes. For example, we are interested in interfacing them with electromechanical oscillators coupled to superconducting circuits and will explore the possibility to cool an oscillator mode to its quantum mechanical ground state by extracting phonons via a coherent exchange of microwave photons with the atoms.

Here, we discuss the prospects of implementing such hybrid systems and present our progress on the construction of a cryogenic setup which allows to interface ultracold atoms with other quantum systems in a 4 K environment. The system combines a closed-cycle cryostat with vibration isolation with a classical room-temperature setup from which ultra-cold atoms will be magnetically transported into the cryo-region. Besides providing the suppression of thermal noise required to study superconducting circuits and electromechanical oscillators near their ground state, the enhanced vacuum conditions due to cryo-pumping will eliminate the need to bake the vacuum system and enable fast exchange and cooling of samples in the experiment region. Moreover, experiments with Rydberg atoms also benefit from enhanced life-times due to the suppression of blackbody induced decay.

Atomic waveguide QED with atomic dimers

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Quantum emitters coupled to a waveguide is a paradigm of quantum optics, whose essential properties are described by waveguide quantum electrodynamics (QED). However, conventional waveguides or photonic crystals are affected by intrinsic internal losses or imperfections that hinder their performance. Here, we study the possibility of observing the typical features of the conventional waveguide QED scenario in a system where the role of the waveguide is played by a one-dimensional subwavelength atomic array. Such a setting features a conceptually simple, clean optical medium that allows, in principle, to eliminate said imperfections. For the emitters that will couple to the atomic waveguide, we propose to use anti-symmetric states of atomic dimers - a pair of closely spaced atoms - as effective two-level systems, which significantly reduces the effect of free-space spontaneous emission. We solve the dynamics of the system with the dimer frequency inside or outside the band of modes of the array. Along with well-known phenomena of collective emission into the guided modes and waveguide-mediated long-range dimer-dimer interactions, we uncover significant non-Markovian corrections which arise from the finiteness of the array and through retardation effects.

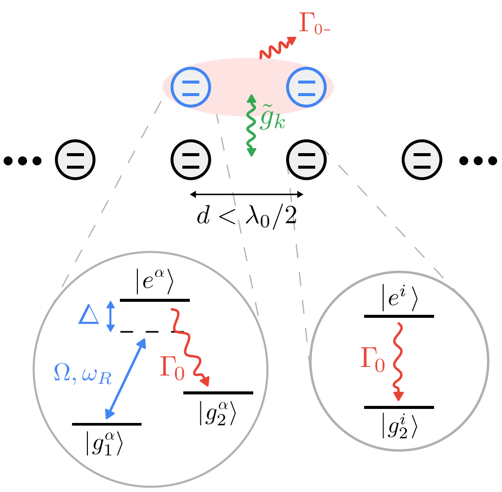

Figure 1 – Schematic representation of the setup studied in this project. The impurity atoms interact with collective states of the atomic chain. The dimers' linewidth is controlled with a Raman transition.

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Bandgap engineering in GaAs/GaAsN core-shell nanowires by post-growth hydrogen implantation

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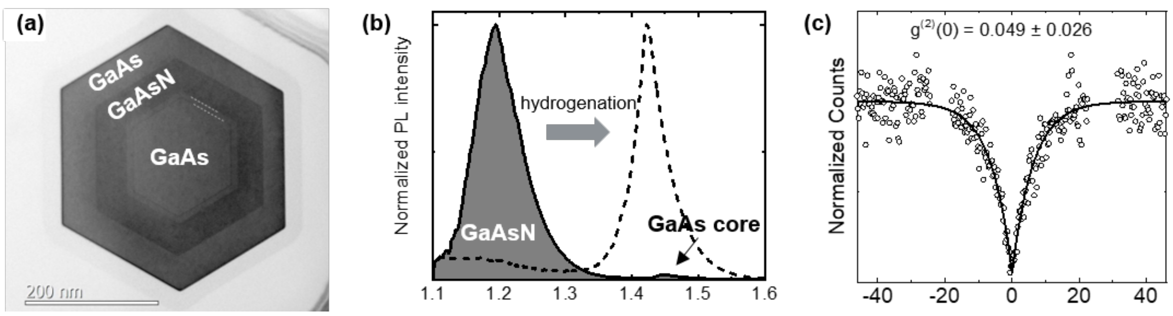
Quantum dots and rings in semiconductor nanowires are valuable assets in the toolbox for quantum optical applications because of their property of being moveable quantum structures. The desired quantum structure can be fabricated and then picked up and placed at the desired location in an optical circuit or cavity. Furthermore, nanowires exhibit other superior properties, such as the ability to incorporate radial or axial heterostructures, low defect density because defects with long-range strain fields, such as point defects, are attracted to nearby surfaces during growth, and intrinsic waveguide and cavity properties that amplify emission and direct it to a desired optical mode for further use. To create these structures, the electronic bandgap must be manipulated at the nanoscale, usually by varying the material composition or crystal phase during growth. While this approach is very powerful, it offers limited control over the size and emission energy of the quantum structure.
Here we demonstrate the bandgap engineering of GaAs/GaAsN nanowires by post-growth hydrogen implantation. The low concentration of N atoms (0.7-3%) generates a perturbation potential that leads to a downshift of the GaAs bandgap energy by up to 400meV. By forming stable N-H complexes, we can shift the bandgap back to the value of GaAs in the regions exposed to low energy H-irradiation. At the same time, we show that this H-implantation is accompanied by a tremendous optical signal increase due to the passivation of surface and interface states. Using μ-Raman and μ-photoluminescence measurements, we investigate the peculiarities of this engineered nanowire system. Moreover, we investigate excitonic lines in thin GaAs/GaAsN nanowires and find a g2 value of 0.05, thus proving the potential of GaAsN nanowires to act as single photon emitters.



Ultrafast excitation exchange in a Maxwell-Fish-Eye lens

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The single-mode Jaynes-Cummings model has been of paramount importance in the development of quantum optics. Recently, also the strong coupling to more than a single mode of an electromagnetic resonator has drawn considerable interest [1]. We investigate how this multimode strong coupling regime can be harnessed to coherently control quantum systems. Specifically, we demonstrate that a Maxwell-Fish-Eye lens [2] can be used to implement a pulsed excitation-exchange between two distant quantum emitters. This periodic exchange is mediated by single photon pulses and can be extended to a photon-exchange between two atomic ensembles, for which the coupling strength is enhanced collectively. Our study illustrates how ideas from classical optics can be used in the realm of multimode strong coupling for applications in quantum technology.

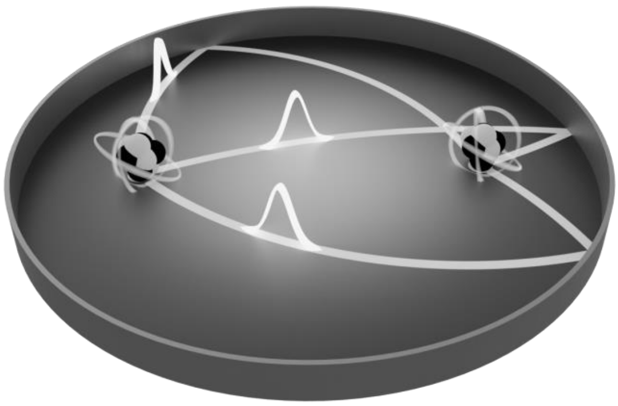

Figure 1: Schematic representation of the excitation exchange. Two atoms are placed in a Maxwell-Fish-Eye lens at opposite positions. Due to the radial refractive index gradient, light rays propagate on circular arcs. Notably, all rays emerging from one atom meet at the antipodal point (three rays illustrated exemplarily). As a result, an excitation that is emitted by one atom as a pulse may refocus at the other atom, and can be reabsorbed.

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Chiral orbital order of interacting bosons without higher bands

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Ultracold atoms loaded into higher Bloch bands provide an elegant setting for realizing manybody quantum states that spontaneously break time-reversal symmetry through the formation of chiral orbital order. The applicability of this strategy remains nonetheless limited due to the finite lifetime of atoms in high-energy bands. Here we introduce an alternative framework, suitable for bosonic gases, which builds on assembling square plaquettes pierced by a π-flux (half a magnetic flux quantum). This setting is shown to be formally equivalent to an interacting bosonic gas loaded into p orbitals, and we explore the consequences of the resulting chiral orbital order, both for weak and strong onsite interactions. We demonstrate the emergence of a chiral superfluid vortex lattice, exhibiting a long-lived gapped collective mode that is characterized by local chiral currents. This chiral superfluid phase is shown to undergo a phase transition to a chiral Mott insulator for sufficiently strong interactions. Our work establishes coupled π-flux plaquettes as a practical route for the emergence of orbital order and chiral phases of matter.

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Tunable negative lens based on gold nanorods

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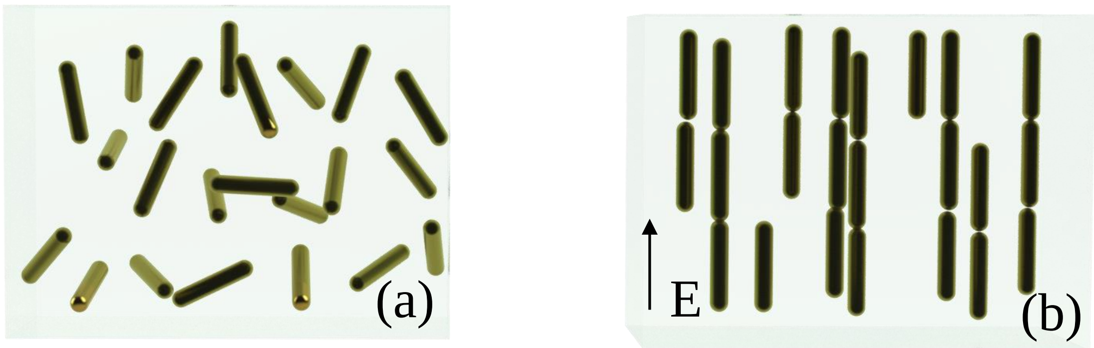
We propose a metamaterial with tunable electromagnetic properties which consists of a colloidal dispersion of gold nanorods in a carrier liquid. The tunability is achieved when the system is subject to an externally applied electric field. It is known that randomly dispersed nanorods (see fig. (a) below, where the applied field is zero) align themselves to the applied electric field when the latter is of sufficient strength (see fig. (b) below). This leads to changes in the dielectric response of the composite material. Here we show that a controllable metamaterial with tunable negative refractive index can be designed due to the field-driven alignment of gold nanorods. We also show that an electromagnetic switch can be conceived of such a dispersion according to the volume fraction of nanorods in the carrier liquid as well as the strength of the external electric field [1].



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Towards Quantum Memories in Noble-Gas Nuclear Spins with Alkali Metal Vapour as Optical Interface

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Quantum memories with storage times well beyond one second will spawn manifold applications in quantum communication and quantum information processing, e.g. as quantum token for secure authentication. Compactness and technological simplicity are key parameters for the memory platform to achieve large-scale applicability. We present our first steps towards a quantum memory with long storage time in a mixture of the noble gas xenon-129 and an alkali metal vapour of caesium-133. A custom glass cell at about room temperature contains both species and is placed inside a table-top magnetic shield with coils for control of magnetic fields. Information will be stored in the collective excitation of nuclear spins of xenon-129, which exhibit hours-long coherence times [1]. Caesium-133 serves as optical interface for signal photons, which we store in a collective spin excitation using EIT [2]. Coherent information transfer to the noble-gas spins is based on spin-exchange collisions and will be controlled by synchronisation of Larmor precession [3].

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Time-frequency quantum metrology

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Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou-Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications. After discussing the spectral engineering of photon pairs, we will discuss the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

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Intensity correlations in the Driven Dicke Model

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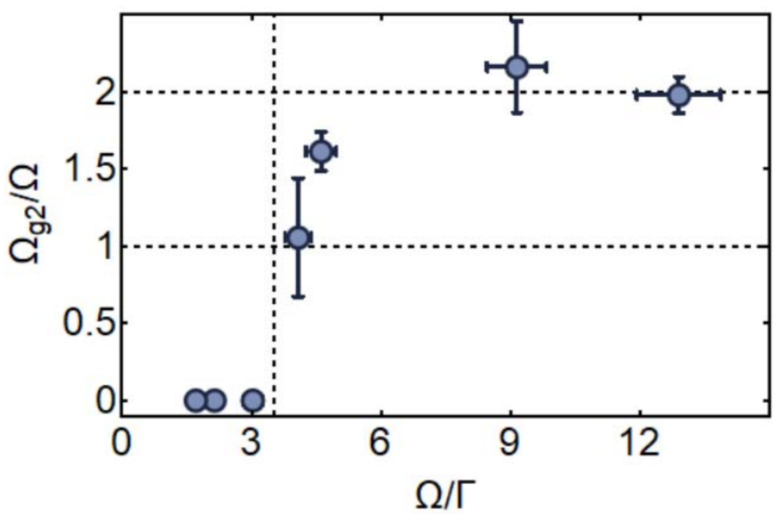
Superradiance originates from the cooperative coupling between an ensemble of emitters and a single radiation mode [1]. In the presence of an external driving laser, the dynamics of the system is described by the so called Driven Dicke model (DDM) [2]. Recently, we have implemented this iconic model laser driving a dense and elongated cloud of cold Rb atoms [3]. To go deeper in the exploration of this model, we report recent measurements aimed to investigate the steady state intensity correlations ($g_2(t)$) of the light emitted by the system into the superradiant mode. We observe the establishment of collective effects in it, manifested as an increasing of the oscillation frequency of $g_2(t)$ with respect to the single atom case. This behaviour was predicted by means of DDM and never observed before [4,5]. Beside its fundamental interest, a pristine investigation of the collective behaviour in $g_2(t)$ might shed a light on the time crystalline nature of this driven-disspative system [6,7].



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Local dissipation effects in the driven-dissipative Dicke phase transition

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The driven Dicke model, wherein an ensemble of atoms is driven by an external field and undergoes collective spontaneous emission due to coupling to a leaky cavity mode, is a paradigmatic model that exhibits a driven dissipative phase transition as a function of driving power. Recently, a highly analogous phase transition was experimentally observed, not in a cavity setting, but rather in a free-space atomic ensemble [1]. Motivated by this, we present our ongoing efforts to better characterize the free-space problem, and understand possible differences compared to the cavity version. We specifically discuss a cavity QED model with weak local dissipation as a minimal model for the free space. We find that the presence of local dissipation dramatically changes the properties of the phase transition. In particular, we present preliminary arguments that suggest that the free-space case might exhibit a smooth crossover rather than a true phase transition in the thermodynamic (large atom number) limit.

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Oscillating Phase Transition in a Chiral Waveguide

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The interaction between a one-dimensional array of atoms with light propagating inside a nearby waveguide offers a new platform for studying many-body quantum phenomena emerging from the long-range coupling between the atoms, which is mediated by the light. One particular class of phenomena that are of interest is that of phase transitions. Is has been predicted that when the atoms couple equally strongly to the left and right propagating modes of the electric field that the system can undergo a phase transition [1, 2], akin to the superradiant phase transition, known from cavity QED [3]. In the phase with low coupling, the system will go towards a steady-state in which the macroscopic spin variables become static. In the other phase however, the macroscopic spin variables start to oscillate instead of going towards a fixed value. We extend this analysis to chiral waveguides, i.e., systems where the atoms can couple differently to the left and right propagating modes. The atoms are modelled using an effective master equation by summing out the waveguide modes. We investigate the phase diagram of the system in terms of the coupling strength and a symmetry parameter describing how symmetric or chiral the system is and see that the oscillations also occur if non-symmetric systems. Given that for an arbitrary chirality, one cannot solve the system analytically, we present numerical approaches to solve the problem. However, since the dimension of the Hilbert space of the atomic system is exponential in the number of atoms, one cannot simply solve the master equation for enough atoms to clearly see the phase transition. As such we need certain numerical approaches that allows us to simulate larger systems. Specifically, we try to use the so-called matrix product states, which have been used to simulate similar systems [4].

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Shaping Free Electrons with Nonlinear Optical Cavity States

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Optical shaping of electron beams fosters many applications ranging from particle acceleration and attosecond bunching to laser-driven phase plates for improved electron microscopy. Most of these examples rely on the inelastic interaction between photons and free electrons, which also has been proposed for probing and shaping quantum optical excitations. This, however, requires a strong electron-light coupling strength as well as control over the optical input and output.

Here, we introduce an integrated photonics microresonators as a suitable platform for efficient electron-light interaction [1] and demonstrate their potential for electron beam modulation using nonlinear optical intracavity states.
We place a fiber-coupled photonic chip-based ring resonator inside a transmission electron microscope (TEM), such that electrons can interact with the optical mode. Characterising the interaction both optically and via electron spectroscopy, we find an efficient coupling facilitated by the resonant field enhancement and velocity matching. When going to higher optical pump powers, the excited nonlinear optical cavity states cause a unique electron beam modulation in energy and space. In the specific case of a dissipative Kerr solitons, we can detect which electrons have interacted with the ultrashort travelling soliton pulse.

While these results may find direct application in the generation of short electron pulses via ultrafast temporal gating, our work also expands the toolbox for electron state shaping. Future studies will investigate how such modulated electron beams might be applied to shape photonic states. At the same time, further improving the underlying single electron single photon interaction strength would render free electrons a suitable probe for quantum optical excitations.

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Dissipative time crystals in an atom-cavity platform

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We are experimentally exploring the light-matter interaction of a Bose-Einstein condensate (BEC) with a single light mode of an ultra-high finesse optical cavity. The key feature of our cavity is the very small field decay rate ($\kappa/2\pi$ = 3.5 kHz), which is in the order of the recoil frequency ($\omega_{rec}/2\pi$ = 3.6 kHz). This leads to a unique situation where cavity field evolves with the same time scale as the atomic density distribution. Pumping the system with a steady state light field, red detuned with respect to the atomic resonance, the Dicke model is implemented including the self-organisation phase transition. Starting in the self-ordered superradient phase and modulating the amplitude of the pump field, we observe a dissipative discrete time crystal, whose signature is a robust subharmonic oscillation between two symmetry-broken states [1]. Modulation of the phase of the pump field give rise to an incommensurate time crystalline behaviour [2]. For a blue-detuned pump light with respect to the atomic resonance, we observe limit cycles. Since the used pump protocol is time-independent, the emergence of a limit cycle phase heralds the breaking of continuous time-translation symmetry [3].

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Bound photon pairs in a symmetric WQED set-up

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Strongly correlated states of photons has been an attractive subject of research in recent several years demonstrating interesting results both in theory [1], and experiment [2]. The fact that the two-level atoms possess an inherent non-linearity allows for two or many photons to exhibit strong photon-photon correlations during the scattering. One of the manifestations of these correlations is the creation of a bound state of photons.

In the presented work we demonstrate how it is possible to create a two-photon bound state that simultaneously resembles some features of a pair of fermions in a simple system: just a pair of qubits that are strongly coupled to a guided mode (see Fig. 1 (a)). The photons in this state tend to be close to each other, but when they are too close, they experience a strong repulsion, leading to antibunching. Using the analytical two-photon scattering theory, we demonstrate that this state is result of a destructive interference between the two bound states each generated by a different scattering channel: one by a local (single atom) nonlinearity, while the other channel is provided by a collective non-linearity of two qubits – when both of them get excited during the scattering.

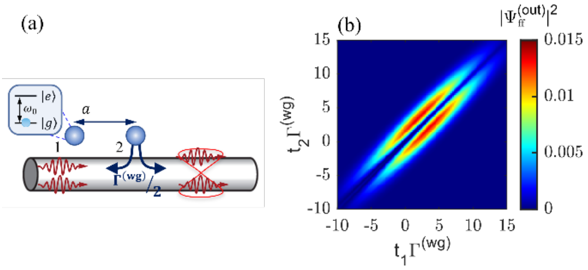

Fig. 1: (a) Scheme of the considered system: a pair of qubits that are $a = 0.25\lambda_0$ apart, and symmetrically coupled to a guided mode, losses out of the waveguide are neglected. A pair of photons in a Fock state with a Gaussian temporal profile scatters off the qubits. (b) The temporal profile of the transmitted wavefunction. The total probability to register two photons being transmitted is around $P{\sim}0.01$.

We believe that our findings are of interest for the research community studying generation of peculiar many-photon states with the unusual quantum statistics.

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Two-photon excitation of exciton-polaritons for direct measurement of the polariton-polariton interaction strength

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Exciton-polaritons are hybridized quasi-particles consisting of a coherent superposition of a quantum well exciton and a cavity photon. They combine the large nonlinearity of the excitonic component with the photonic component whose potential can easily be engineered in micropillar lattices, and which enables site-selective excitation and detection [1]. These properties have enabled the exploration of fascinating nonlinear phenomena such as Bose-Einstein condensation, superfluidity, parametric instabilities…. However, up to now, most experiments with exciton-polaritons have been conducted in a regime where the system's properties can be well described by a mean-field approach, where the nonlinearity amounts to the polariton-polariton interaction energy multiplied by the average polariton density. Yet, reaching a regime of strongly interacting polaritons would offer unprecedented possibilities to study strongly-correlated phases of light [2]. To reach such a regime, large nonlinearities at the single-photon level are required. Here, in a first step en route to strongly-interacting exciton-polaritons, we demonstrate a novel nondegenerate two-photon excitation scheme of exciton-polaritons in a micropillar. When performed in the few-photon regime, this excitation scheme should allow to extract spectroscopically the two-body interaction energy without requiring a precise polariton density calibration, which usually leads to large uncertainties in measurements of the interaction energy conducted in the mean-field regime [3]. Moreover, using this novel excitation scheme, we anticipate non-trivial temporal correlations for the photons escaping the cavity. The demonstrated excitation scheme will thus serve as a crucial tool to systematically optimize and enhance the polariton interactions and to achieve strongly-interacting exciton-polaritons.

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Strongly Interacting Polaritons in Moiré Quantum Materials

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Atomically thin solid-state systems such as bilayers of transition metal dichalcogenides (TMDCs) offer a new but rapidly evolving platform for quantum nonlinear optics. The enormous interest in these systems stems from the possibility to control the properties of these quantum materials which facilitates the study fascinating phenomena such as superconductivity or topological effects that occur along with the emergence of flat bands due to a so-called moiré superlattice. This superstructure forms either due to a lattice mismatch between the two monolayers or a slight relative twist angle of the two layers. Interestingly, the period of such moiré lattices is on the order of a few tens of nanometers extending over many unit cells of the underlying lattice of the monolayers. This opens up a new regime between real solid-state systems with Ångstrøm distances and atomic arrays with lattice spacings of a few hundred nanometers. In such a deep sub-wavelength regime, collective effects of light-matter interaction are expected to be much more pronounced than in atomic arrays and arrays of moiré excitons acting as quantum dots have been realised experimentally. A particularly interesting aspect of twisted bilayers of TMDCs is the peculiar band structure of compounds such as $MoSe_2/WS_2$ which allows for a resonant hybridisation of excitons that form within each layer (intralayer excitons) and excitons that form between the layers (interlayer excitons). While the intralayer excitons strongly couple to the external light field, the interlayer excitons are indirect and possess long lifetimes that are tuneable via the twist angle. Furthermore, due to their strong mutual dipole-dipole interactions they are promising candidates to engineer strong and long-range synthetic interactions between exciton-polaritons.

Here, we use an effective Bose-Hubbard model for the hybridised excitons [1] and study the appearance of repulsively bound states as a function of the twist angle. Then, we couple the system to a cavity mode and study the scattering between the exciton-polaritons in the lowest band. We show that the emergence of a moiré flat band together with the repulsive dipole-dipole interactions leads to a scattering resonance between excitons and polaritons.

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Higher-order mean-field theory of chiral waveguide QED

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Waveguide QED with cold atoms provides a potent platform for the study of non-equilibrium, many-body, and open-system quantum dynamics. Even with weak coupling and strong photon loss, the collective enhancement of light-atom interactions leads to strong correlations of photons arising in transmission, as shown in recent experiments. Here we apply an improved mean-field theory based on higher-order cumulant expansions to describe the experimentally relevant, but theoretically elusive, regime of weak coupling and strong driving of large ensembles. We determine the transmitted power, squeezing spectra and the degree of second-order coherence, and systematically check the convergence of the results by comparing expansions that truncate cumulants of few-particle correlations at increasing order. This reveals the important role of many-body and long-range correlations between atoms in steady state. Our approach allows to quantify the trade-off between anti-bunching and output power in previously inaccessible parameter regimes. Calculated squeezing spectra show good agreement with measured data, as we present here.

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Deterministic Free-Propagating Photonic Qubits with Negative Wigner Functions

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Engineering quantum states of free-propagating light is of paramount importance for quantum technologies. Coherent states ubiquitous in classical and quantum communications, squeezed states used in quantum sensing, and even highly-entangled cluster states studied in the context of quantum computing [1] can be produced deterministically, but they obey quasi-classical optical field statistics described by Gaussian, positive Wigner functions. Fully harnessing the potential of many quantum engineering protocols requires using non-Gaussian Wigner-negative states [2], so far produced using intrinsically probabilistic methods.

We will present the first fully-deterministic preparation of non-Gaussian Wigner-negative free-propagating optical quantum states [3]. In our setup, a small atomic cloud placed inside a medium-finesse optical cavity and driven to a highly-excited Rydberg state acts as a single two-level collective "superatom" [4]. We coherently control its internal state, then map it onto a free-propagating light mode to produce an optical qubit $\cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,|1\rangle$ encoded as a quantum superposition of 0 and 1 photons. Its single-photon character is revealed by photon correlation measurements showing strong antibunching with a residual 0.5% probability of having two photons per pulse. The generated states are emitted in the desired spatio-temporal mode with a high 60% efficiency. Using an homodyne tomography we measure the density matrix leading to the Wigner functions displayed on Fig. 1. In agreement with theoretical predictions, these functions are quadrature-squeezed for small qubit rotation angles θ, and develop a negative region when θ approaches π and the one-photon component becomes dominant. Our platform featuring a new approach of cavity quantum electrodynamics realizes a long sought goal of quantum optics, while holding promises for photonic quantum engineering applications.

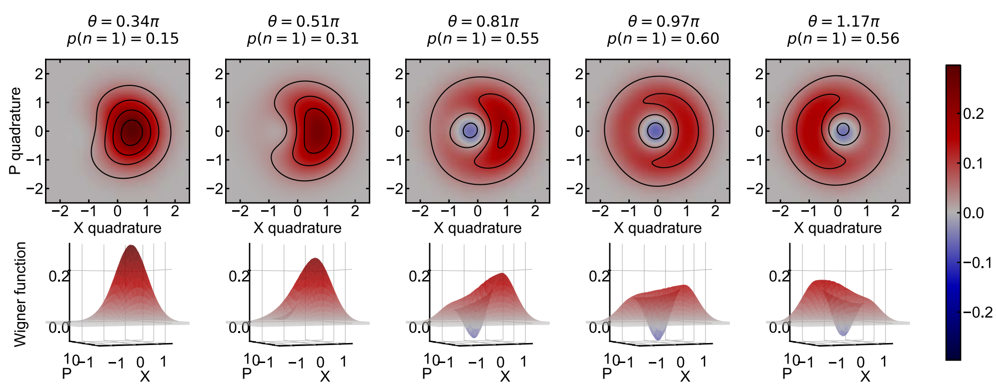

FIGURE 1. Homodyne tomography of the optical qubit, first and second rows show two- and three-dimensional color-mapped representations of Wigner functions over quadrature phase space, sorted column-wise by increasing qubit rotation angle θ with the measure of one-photon population $p(n=1)$ of the density matrix

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Experimental Study of the Spin Properties of Cold Atomic Mixture

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Ultracold atomic systems are ideal testbeds for exploring quantum effects. Most of the available cold atom detection techniques are destructive in nature. We report a novel technique based on Spin Noise Spectroscopy (SNS) which is a non-perturbative probe of the dynamical spin properties of matter and can be employed to explore Quantum Phase Transition in Ultra-cold gases. We demonstrate the detection of intrinsic spin-coherence from an ensemble of cold atoms using Faraday rotation fluctuation measurements [1]. The main goal of this work is to investigate the quantum properties in an ensemble of ultracold atoms. The same technique can be used to demonstrate high-resolution and time-resolved magnetometry. I shall also present our recently developed cold-atom mixture experimental set up and its performance where the next phase of this spin coherence experiment will be performed. We have a system of cold dual species Sodium and Potassium magneto-optical trap (MOT) which captures more than 3×10^{10} ^{39}K atoms and 5.8×10^{8} ^{23}Na atoms in the 3DMOT simultaneously from the individual 2D^{+}MOTs with the capture rate of 5×10^{10} atoms/sec and 3.5×10^{8} atoms/sec for ^{39}K and ^{23}Na, respectively. Such an experimental set up is capable of exploring the spin-spin interactions between the mass imbalance cold atomic ensembles. A particular advantage in this case will be the controllability over the inter-species spin interactions. Also, unlike the standard absorption and fluorescence imaging techniques, SNS measurements in cold atomic systems will be a non-destructive imaging tool without hugely affecting the quantum states of the trapped atoms.

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Shielding atoms from losses in strontium magneto-optical traps

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We present a method to decrease losses in magneto-optical traps (MOT) of strontium atoms operating on the 461 nm transition. This method is based on the resonant driving of the $^1S_0 \rightarrow {}^3P_1$ intercombination line at 689 nm, which continuously populates a short-lived reservoir state and, as expected from a theoretical model, partially shields the atomic cloud from losses arising in the 461 nm cooling cycle. By controlling the population in the reservoir state, we control an overall loss rate and decrease the losses by a factor of two when the transition is saturated, resulting in a factor of two enhancement in the atom number of a steady-state MOT. Our theoretical model predicts that the shielding is insensitive to the type of losses and can be applied to MOTs with dominating or negligible light-assisted collisions induced losses. We demonstrate it experimentally and successfully apply the shielding to magneto-optical traps of all stable isotopes of strontium. We formulate the prerequisites of the shielding and show that they are not specific to strontium, and thus the method could be extended to other atomic species.

Resolving a single-atom “thermodynamic limit” in cavity QED: photon correlations and field distributions in the strong-coupling regime

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In the open driven Jaynes-Cummings (JC) model, multi-photon resonances occur as a result of the “quantum jumpiness” in matter [1], for a scattering process fundamentally affected by the inputs and outputs – information is read off two channels linked to a system comprising a two-level atom strongly coupled to a resonant coherently driven cavity mode. The special role of quantum fluctuations in this model is captured by the breakdown of photon blockade by means of a dissipative quantum phase transition [2, 3]. To resolve the associated strong-coupling “thermodynamic” limit [4], we focus on the buildup and collapse of phase-space multimodality for weak driving, where a perturbative treatment is possible. Correlation functions of the forwards and side-scattered photons provide an alternative perspective, uncovering conditional dynamics that are shaped by features unique to the ladder of JC eigenstates. We then meet the region of amplitude bistability for a drive amplitude of the same order of magnitude as the light-matter coupling strength. This brings us to the critical point of a second-order quantum phase transition on resonance, where the quantum and semiclassical pictures are once more contrasted as we go through the collapse of the JC quasienergy spectrum.

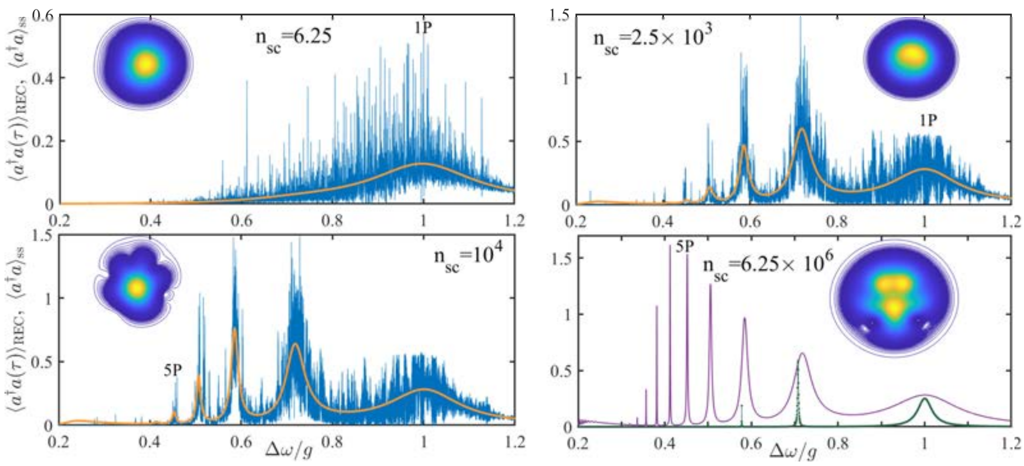

Figure : **Persistence of photon blockade [4]** Steady-state (master equation) and time-varying conditional (single realizations modelling heterodyne measurement) cavity photon number for a scaled cavity-drive detuning $\Delta\omega/g$ scanned across the regime of photon blockade. Higher-order resonances appear with increasing system-size parameter $n_{\rm sc}$. The insets depict the Wigner function of the cavity field at the vacuum Rabi resonance (top row) and the five-photon resonance (bottom row).

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Quantum-memory-based time-frequency processor

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Many quantum information protocols are enabled by the manipulation and detection of photonic spectro-temporal modes. The common approach for spectro-temporal processing is to leverage space-time duality by employing electro-optic modulation and highly-dispersive fibers implementing a temporal imaging setup. A glorified example is to perform a frequency-to-time mapping—a Fourier transform—that enables spectral measurements using time-resolving detectors. More sophisticated examples allow time-frequency mode-sorting that can lead to spectral or temporal superresolution measurements. Such state-of-the-art solutions are all well suited for broadband (>100 GHz) systems, such as quantum dots or other solid-state-based setups. Feasible implementations of the protocols merging flexibility of atomic systems and temporal processing capabilities inherently require an ability to manipulate and detect temporal photonic modes with a spectral and temporal resolution matched to the narrowband atomic emission. We demonstrate a novel approach to spectro-temporal processing working in a previously unexplored regime of narrowband atomic emission [1]. Our method is based on cold-atoms-based gradient-echo quantum memory (GEM) for light that maps incoming light pulses onto atomic coherence (spin waves). We combine the GEM with a technique of spin wave phase modulation, that employs a spatially shaped laser beam that causes a spatially varying light shift of the atomic levels. This way we can imprint almost arbitrary phase profiles onto the coherence and for example, achieve an ultra-large group-delay dispersion for an optical pulse stored in the coherence. Combining this with a simple acousto-optic modulation, we realize far-field temporal imaging for a 1 MHz bandwidth with a resolution of <20 kHz. Moreover, with a more advanced protocol, we are able to demonstrate a super-resolution spectrometer that can resolve frequency differences of two emitters way below the Fourier limit [2].

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Collective Radiative Interactions of Many-Particle Systems in the Discrete Truncated Wigner Approximation

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In a recent work [1] we have extended the Discrete Truncated Wigner Approximation, which provides a semiclassical and numerically efficient approximation to the dynamics of an interacting ensemble of two-level systems in the Wigner phase space, to dephasing and spontaneous emission.
Here we discuss the application of this approach to collective radiative interactions between atoms such as Dicke superradiance, collective emission processes in Cavity QED and atomic arrays.
We show that the correspondence rules of collective spin operators attain a simple approximate form for highly cooperative atom-field interactions. This allows us to derive approximate and numerically inexpensive stochastic differential equations for rather general Hamiltonians and linear Lindblad generators.
For the example of the totally symmetric Dicke decay, which is exactly solvable, we find near perfect agreement, but show that the approach fails for subradiant phases. Finally, we demonstrate the applicability of our theory by investigating the dynamics of a coherently driven gas in a harmonic trap and of atomic arrays at subwavelength distances and their superradiant properties.

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Quantum simulation with circular states of strontium

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Quantum simulation is one of the main developing quantum technologies. The goal is to simulate the dynamics of many-body system with another quantum system, in which we can control every parameter.

Many systems are being investigated to implement a quantum simulator (superconducting qubits, trapped ions, cold atoms in optical lattices…). Rydberg atoms trapped in optical tweezers, in particular, is a very versatile platform being developed in several groups. Up to hundreds of ground states atoms are trapped in optical tweezers and re-arrange in arrays with arbitrary geometry configuration. The ground state atoms are then transferred by laser excitation to low angular momentum Rydberg states. These highly excited states exhibit a very strong dipole-dipole coupling between neighboring atoms that can be tuned by adjusting the array orientation or by applying microwave dressing. This enables to simulate arbitrary spin Hamiltonians, or study their many-body dynamics. In our group we use Circular Rydberg states, which are states with maximum angular momentum [1]. When placed in a cryogenic environment that suppress black-body radiation, the lifetime of circular states can reach up to tens of milliseconds as opposed to low-angular momentum Rydberg states that have a lifetime in the 100 µs range.

Alkali circular states can be trapped with focused laser beams using the ponderomotive potential of the almost free Rydberg electron, making it possible to study the simulated spin dynamics over long time scale. In the case of alkaline-earth atoms however, the large polarizability of the ionic core allows to directly trap the circular state in optical tweezer. The optical transitions of the ionic core also provide a way to detect the Rydberg atoms. Furthermore, if the core electron is in an excited state with a non-zero electric quadrupole moment, its coupling to the Rydberg electron will induce an energy shift in the ionic core energy levels. This energy shift depends on the principal quantum number n of the circular state. It can be measured by Raman spectroscopy of the ionic core, opening the way to perform QND measurement of the circular state [2].

The goal of my PhD thesis is to develop a new experiment, in which we trap single atoms of circular state of strontium in optical tweezers and use the coupling between the two electrons to perform QND measurement of the circular state or quantum gates operations with the long-term goal of creating a quantum simulator.

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Cavity Jahn-Teller Polaritons in Molecules

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The control and exploitation of angular momentum and helicity of cavity photons constitutes one of the most active frontiers in the fields of polaritonic materials science [1] and polaritonic chemistry [2,3]. In our work, we have investigated the fundamental coupling mechanism of (+/−)-circular polarizations of the trapped-light modes originating from the vibronic interactions within the Jahn-Teller (JT) active molecules or material inside a Fabry-Perot cavity [4]. The mechanism results in the efficient exchange of photonic and vibronic angular momenta between the light and the matter. It leads to a new type of polaritonic state with mixed polarization character, namely, the JT polariton. Due to the photonic-vibronic coupling, the magnitude and direction of the cavity polarization varies for different eigenstates of the cavity- molecule system. This type of light-matter coupling results in polarization inverted states in the polaritonic system: states that can be reached resonantly with either right or left circularly polarized light, but which are characterized by a cavity-photon polarization opposite to the external fields used to excite the system.

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Multiphoton processes in atomic systems mediated by optical nanofibres

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Optical nanofibers – very thin, tapered optical fibers where the waist diameter is less than the propagating light wavelength – have been shown to be very useful tools for atom-light interactions. Their small size and relative ease of integration into optical fiber-based experimental setups, in addition to their minimal perturbation on magneto-optically trapped cold atoms, have ensured their adoption into cold atom physics. Here, we will discuss some recent applications of optical nanofibers to manipulate, trap, and control cold ^{87}Rb atoms in ground or Rydberg states. We will present some recent experimental and theoretical results related to the interactions between the atoms and the optical nanofiber field and introduce some of the limitations observed.

Optical Fractional Fourier Transform in the time-frequency domain experimentally demonstrated via a quantum-memory setup.

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Fractional Fourier Transform (FrFT) has a number of applications ranging from noise reduction[1] to radar science and mode sorting of light[2]. It has an intuitive meaning when we represent it as a rotation of chronocyclic Wigner function in time-frequency space. This can be achieved by applying specific time and frequency quadratic phases to the input signal by means of frequency modulation and AC-Stark shift applied to light stored as atomic coherence in the Gradient Echo Memory. Previous experiments show that quantum memories allow for versatile processing of quantum states of light[3] including super-resolved spectroscopy[4] and Fourier transform[5]. We expand that idea and present our experimental setup that was used to perform FrFT on two-pulse “Schroedinger cat” states and Hermite-Gauss modes (eigenfunctions of FrFT). We are the first to implement the FrFT in the time-frequency domain. This achievement opens up new avenues, in particular, tailored noise reduction protocols could now be implemented in the optical domain. Our setup allows for manipulation of signals with bandwidth reaching 1 MHz and duration of 25 μs, allowing operation with ultra narrow band light compatible with atomic and optomechanical systems.

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Theoretical analysis of mode-sorting techniques in the time-frequency domain

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Spatial and spectral mode sorting of optical pulses has recently become a subject of intensified research. It has already been shown that spectral mode sorting allows for achieving the superresolution for two spectrally overlapping optical pulses, which can play a crucial role in microscopy and astronomy. In general mode sorting is the decomposition of the optical pulse into Hermite-Gauss or Laguerre-Gauss modes, by imposing arbitrary phases both in the time and frequency domain in a specific sequence. Although multiple optical setups performing such procedures were shown, the theory behind mode sorting and its limitations is still a subject of discussion. We would like to present our model of generalized mode sorting and discuss its theoretical and experimental limitations. Moreover we would like to present different schemes of mode-sorting utilizing gradient echo memory (GEM) protocol, which allows for imparting arbitrary phases both in time and frequency domains.

Quantum nonlinear metasurfaces from dual arrays of ultracold atoms

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Optical interfaces with sub-wavelength patterns make it possible to manipulate light waves beyond the typical capabilities of ordinary optical media. Sub-wavelength arrays of ultracold atoms enable such transformations at very low photon losses. We have shown how the coupling of light to more than a single atomic array can expand these perspectives into the domain of quantum nonlinear optics. While a single array transmits and reflects light in a highly coherent but largely linear fashion, the combination of two arrays is found to induce strong photon-photon interactions that can convert an incoming classical beam into strongly correlated photonic states. Such quantum metasurfaces open up new possibilities for coherently generating and manipulating nonclassical light, and exploring quantum many-body phenomena in two-dimensional systems of strongly interacting photons. While these results have been found through numerically solving a master equation and using the input-output formalism, we are now developing a more analytical approach based on Green's functions to find exact analytical expressions for the photonic correlations.

Continuous-wave microwave-to-optical conversion beyond the blackbody radiation noise using room-temperature atoms

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Bidirectional microwave-optical conversion at the level of single photons would enable the interconnection of remote quantum devices via optical links. This would bridge the worlds of quantum microwave devices such as superconducting qubits, and quantum optics at telecom or visible wavelengths - particularly well suited for long-distance communication. Achieving these grand goals will undoubtedly require complex devices. One simple system stands out among many proposals, as *Rydberg atoms* are coupled to both light and microwaves, allowing for the coupling of the two domains. In particular, hot atomic vapors require minimum overhead and are readily used for clocks, magnetometry, and quantum memories.

We provide an experimental demonstration of microwave-to-optical conversion using hot atoms. The system allows the upconversion of 14 GHz microwaves to an optical signal at 776 nm via a six-wave mixing process. Remarkably, the method achieves about 1% photon-to-photon efficiency (calculated locally, without considering diffraction yet) and a very low intrinsic noise owing to a specific mixing process selected. The geometry is also designed to partially cancel Doppler broadenings. This allows us to achieve almost 60 dB of dynamic range, but also directly observe coherently upconverted thermal blackbody radiation, as witnessed by direct single-photon counting and observation of thermal second-order correlation close to 2, and an HBT-type interference effect between microwave coherent and thermal state. These results suggest that even at room temperature the demonstrated method, while not quite ready for superconducting qubits, may be employed for sensing very weak microwaves in communication, radioastronomy, or radar applications, effectively achieving noise temperatures much lower than state-of-the-art amplified, even in cryogenic conditions. A qualitative advantage stems from effectively using photon counting of microwaves at room temperature. For future integration of microwave cavities, we could also cooperatively suppress room-temperature thermal noise and reach towards quantum-electrodynamic effects at room temperature.

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Vibrational energy transfer between trapped atoms via Rydberg Excitation

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The study of heat transfer between spatially separated ultracold atoms serves as a fundamental probe of thermodynamics of mesoscopic quantum systems [1,2]. To study the basic dynamics of this heat transfer, we consider three collinear harmonically trapped ultracold atoms. Coupling the central atom to a high-lying Rydberg s-state ($l=0$) creates interactions between the distant atoms mediated by the scattering of the Rydberg electron off of the trapped atoms. We numerically study the dynamics of an excited oscillator state in this Rydberg-coupled system. It turns out that the time scale of excitation transfer dynamics is smaller than the lifetime of the Rydberg state thus enabling experimental observation. The dynamics of multi-phonon excitation transfer is significantly affected by changing the harmonic trapping frequency of the Rydberg excited atom with respect to that of other two atoms.

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Light-matter interaction at the transition between cavity and waveguide QED

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Experiments based on cavity quantum electrodynamics (QED) are widely used to study the interaction of a light field with a discrete frequency spectrum and emitters. More recently, the field of waveguide QED has attracted interest due to the strong interaction between propagating photons and emitters that can be obtained in nanophotonic waveguides, where a continuum of frequency modes is allowed. Both cavity and waveguide QED share the common goal of harnessing and deepening the understanding of light-matter coupling. However, they often rely on very different experimental set-ups and theoretical descriptions. Here, we experimentally investigate the transition from cavity to waveguide QED with an ensemble of cold atoms that is coupled to a fiber-ring resonator, which contains a nanofiber section [1]. By varying the length of the resonator from a few meters to several tens of meters, we tailor the spectral density of modes of the resonator while remaining in the strong coupling regime. We demonstrate that for progressively longer resonators, the paradigmatic Rabi oscillations of cavity QED gradually vanish, while non-Markovian features reminiscent of waveguide QED appear.

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Polymer membrane resonators in fiber Fabry-Perot cavities

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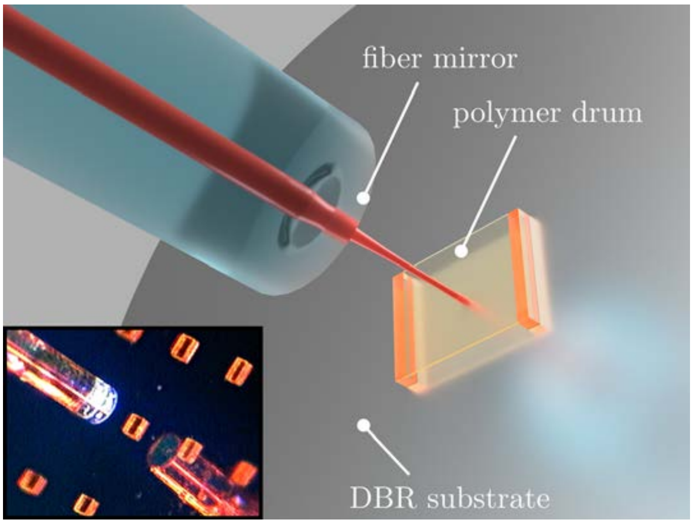
Micro- and nanophotonic systems have demonstrated record coupling strength to mechanical resonator systems, but require elaborate techniques for interfacing. This limits their scaling towards larger systems comprised of many mechanical and optical resonators. Here, we demonstrate a directly fiber-coupled, tunable and highly flexible platform for cavity optomechanics [1]. It is based on 3D laser written polymer structures that are directly integrated into fiber Fabry-Perot cavities. Our experiments show vacuum coupling strengths of $\gtrsim$ 30 kHz to the megahertz-frequency fundamental flexural mode. This allows us to optomechanically tune the mechanical resonance frequency by tens of kHz exceeding both the mechanical resonance frequency disorder and linewidth at cryogenic temperatures. The ease of interfacing the system through the direct fiber coupling, its scaling capabilities to larger systems with coupled resonators, and the possible integration with other experiments makes it a promising platform for upcoming challenges in cavity optomechanics. Applications like fiber-tip-integrated accelerometers, directly fiber-coupled systems for microwave-to-optics conversion, or interfaces for large systems of coupled mechanical resonators are envisioned.



Overview of the experiment setup. A fiber mirror hovers above a distributed Bragg reflector substrate with 3D direct laser written mechanical resonators (fiber-∅ 125 µm). The inset shows a microscope image of the cavity with mechanical resonators.

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Giant Cross Kerr Effect in Cuprous Oxide

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Within the semiconductor cuprous oxide (Cu_2O) electron hole pairs can be excited into highly excited states known as Rydberg excitons. Much like their atomic cousins, many of their properties become exaggerated with increasing principal quantum number; such as physical extent and dipole moments. Following observations of excitonic states up to n = 25 [1], interest in this material as a platform for controlling light has expanded greatly. This has included observations of the Rydberg Blockade [2], Self-Kerr effect [3] and proposals for use as a single photon sources [4].

Here, we take advantage of the microwave energy spacing between Rydberg states, as well as their large dipole moments, to couple such states to one another. We apply strong microwave fields across a sample of Cu_2O and observe sidebands separated from the pump light by twice the microwave frequency, which is signature of a Cross-Kerr effect. By examining the microwave power dependence of these sidebands a Kerr coefficient of ~1 m/V^2 has been obtained, 10^{12} times larger than that of the archetypal Kerr medium nitrobenzene.

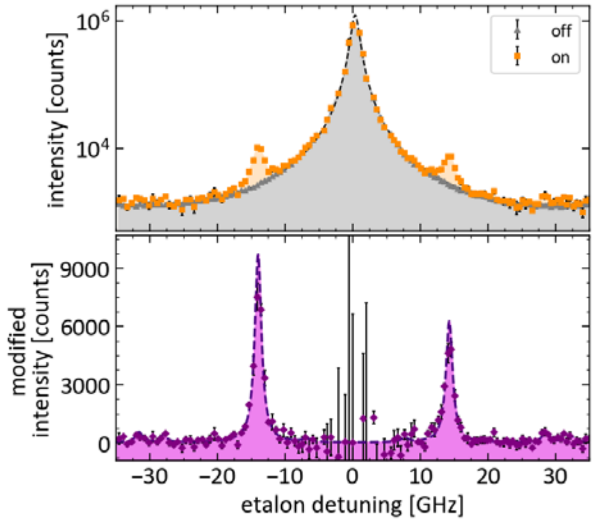

Fig. 1 – Response of a sample of Cu_2O with a 160 mW, 7 GHz microwave signal applied across it.

Top: intensity with microwaves on and off. **Bottom**: intensity of the microwave signal with the carrier signal subtracted. Sidebands are clearly visible 14 GHz away from the carrier, twice the driving microwave signal. This is a signature of a Cross-Kerr effect.

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Towards time-bin entangled photon cluster states

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Following the path towards the second quantum revolution, developments in different fields of quantum technologies such as quantum computing, quantum communication and quantum sensing are evolving rapidly. Single photons are ideal carriers of information due to the lack of interaction with each other. However, manipulating and controlling them for quantum computing becomes a difficult task. One-way quantum computation introduced by Raussendorf and Briegel in 2001 [1] overcomes this challenge by avoiding two-qubit interaction and instead uses a highly entangled state called “Cluster state” as an initial source. Together with a feed forwarded single qubit measurement a scalable universal quantum computer can be implemented using these initial cluster states. The generation of highly entangled cluster states up to a few photons is already reported in many publications [2]. The aim of the project is to initially realize a cluster state of few photons which are time-bin encoded (early and late time-bins) in optical fibres. This encoding avoids a polarization bias, which is challenging to avoid in light guiding fibres or waveguides. The rate of a successful fusion is highly dependent on the minimization of loss and photon-number resolved heralding of the fusion gates. To ensure the generation of a highly entangled cluster state, the photon pair sources should be characterized. The source used in this project is a type-II nonlinear periodically-poled LiNbO3 waveguide with photon-pairs generated at 1560 nm [3]. The spectral purity and the heralding efficiency of the photon pair source is measured at this point in the project which suggests the source is sufficiently good for generation of time-bin entangled cluster states. Moreover, a time-multiplexed detector [4] is being developed for a quasi-photon number resolving detection which is needed for heralding a successful fusion. A time-bin entangled cluster state in fibre with an acceptable generation rate can pave the way towards a universal quantum computer using the one-way quantum computing scheme. This structure can be integrated better into photonic chips which is scalable and makes this approach a very suitable candidate for future commercial products.

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The Quantum Wigner-Smith Operator: Micromanipulation, Metrology and Vacuum Forces

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We introduce the quantum Wigner-Smith (QWS) operator, a Hermitian operator describing the interaction between the spatial as well as the quantum degrees of freedom of light and a local classical parameter of a linear, but otherwise arbitrarily complex scattering medium through which the light propagates. The QWS operator builds a bridge between quantum micromanipulation, vacuum forces and quantum metrology on the one side, and the formalism of classical scattering matrices, which are experimentally measurable in a noninvasive manner, on the other side. We show how to design protocols for optimal micromanipulation as well as for optimal parameter estimation by shaping both the spatial and the quantum degrees of freedom of light. Also, the forces of the quantum vacuum naturally emerge from the formalism.

Exact solution for quantum strong long-range models using a generalized Hubbard–Stratonovich transformation from cavity QED

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The field of cavity qed materials seeks to modify the properties of bulk materials by coupling them to an electromagnetic cavity at equilibrium. When the material is, e.g., composed of magnetic dipoles, the resulting system is described by a generalized Dicke model. Under certain conditions, the cavity modes can be traced out, leaving a spin Hamiltonian with cavity-mediated (effective) spin-spin interactions [1]. Here, we leverage this result to study the relationship between the effective spin model and the underlying Dicke model. We reverse the mapping and use it as a generalized Hubbard–Stratonovich transformation. We show that long-range quantum models can be mapped exactly to generalized Dicke models and use this result to provide an analytical solution in the thermodynamic limit. We illustrate the method on the Ising chain in transverse field. The critical behaviour is found to be universal for all strong long-range models and lattice dimensionalities, in agreement with previous numerical results [2]. The expression for the order parameter is equivalent to the one provided by mean-field theory, proving the exactness of the later. Finally, we study the algebraic decay of correlations and characterize its dependence on the range of interactions in the full phase diagram.

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Tailoring photon statistics with an atom-based two-photon interferometer

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Controlling the photon statistics of light is paramount for quantum science and technologies. Recently, we demonstrated that transmitting resonant laser light past an ensemble of two-level emitters can result in a stream of single photons or excess photon pairs. This transformation is due to quantum interference between the transmitted and incoherently scattered two-photon component. Here, using the dispersion of the atomic medium, we actively control the relative quantum phase between these two components [1]. We thereby realize a tunable two-photon interferometer and observe interference fringes in the normalized photon coincidence rate, varying from antibunching to bunching. Beyond the fundamental insight that the quantum phase between incoherent and coherent light can be tuned and dictates photon statistics, our results lend themselves to the development of novel quantum light sources.

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Dynamical phases in an atom-cavity system: From time crystals to dark states

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Ultracold atoms placed inside a high finesse optical cavity, which are continuously pumped or periodically driven display very rich phase diagrams. We specifically discover non-equilibrium phases called time crystals. Time crystals are classified as discrete or continuous depending on whether they spontaneously break discrete or continuous time translation symmetry. First, we study an emergent limit cycle phase for a blue-detuned pump and show that the phase of the oscillations are random for different realizations, hence this dynamical many-body state spontaneously breaks continuous time translation robustness of this state against temporal noise and its stability in the limit of large particle numbers, classifying this state as a continuous time crystal [1]. On the other hand, if we periodically drive the amplitude of the pump in-situ observed from the light phase of the cavity photons. This state corresponds to a dissipative time crystal [2,3]. Finally, phase shaking of the pump beam can lead to an incommensurate time crystal [4]. The non-integer subharmonic oscillatory motion corresponds to dynamical switching between symmetry-broken states, which are nonequilibrium bond ordered density wave states. We map the system onto a parametrically driven dissipative three-level Dicke model [5] and present the experimental realization [6]. For strong driving, we further show that this state is only metastable and relaxes into a dark state. We show that this stationary subradiant state, with respect to the pump lattice, can be understood as a Bose-Einstein condensate excited to the second Bloch band with an order parameter composed of p-orbitals with staggered local phases [7]. Employing a semiclassical phase-space representation for the dissipative quantum dynamics, we confirm the rigidity and persistence of the various time crystalline phases, namely the continuous, dissipative, and incommensurate time crystals, as well as the dark state.

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Quantum electrodynamics of intense laser-matter interactions: A tool for quantum state engineering

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Intense laser-matter interactions are at the center of interest in research and technology since the development of high power lasers. They have been widely used for fundamental studies in atomic, molecular, and optical physics, and they are at the core of attosecond physics and ultrafast opto-electronics. Although the majority of these studies have been successfully described using classical electromagnetic fields, recent investigations based on fully quantized approaches have shown that intense laser-atom interactions can be used for the generation of controllable high-photon-number entangled coherent states and coherent state superposition [1-5]. We provide a comprehensive fully quantized description of intense laser-atom interactions. We elaborate on the processes of high-harmonic generation, above-threshold-ionization, and we discuss new phenomena that cannot be revealed within the context of semi-classical theories. We provide the description for conditioning the light field on different electronic processes, and their consequences for quantum state engineering of light [4,5]. Finally, we discuss the extension of the approach to more complex materials, and the impact to quantum technologies for a new photonic platform composed by the symbiosis of attosecond physics and quantum information science.

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Distribution of Engineered Entangled States across a field installed Metropolitan Fiber Network

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Entanglement is a key resource for quantum communication and computation. Distribution of entangled particles to spatially separated nodes, is essential for such communication and for distributed quantum computations. Work towards the distribution of both time-bin and polarization entanglement in telecom C-band photons propagated through existing metropolitan telecom dark-fibre network. Current fibres offer looped connectivity with total distance 52km and propagation losses of 19.6dB with excellent intrinsic polarisation stability. Degenerate Spontaneous parametric down conversion (SPDC) with 780nm pump used to generate entanglement at 1560nm. Ultra-low loss periodically polled Lithium Niobite resonant waveguides provides telecom photons free of spectral correlations and a source of heralded pure single photons, for maximum visibility of HOM type interference between independent sources required for entanglement swapping.[1][2]

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Observation of superradiant bursts in waveguide QED

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Dicke superradiance describes the collective decay dynamics of a fully inverted ensemble of two-level atoms. There, the atoms emit light in the form of a short, intense burst due to a spontaneous synchronization of the atomic dipoles. Typically, to observe this phenomenon, the atoms must be placed in close vicinity of each other. In contrast, here we experimentally observe superradiant burst dynamics with a one-dimensional ensemble of atoms that extends over thousands of optical wavelengths. This is enabled by coupling the atoms to a nanophotonic waveguide, which mediates long-range dipole-dipole interactions between the emitters. The burst occurs above a threshold atom number, and its peak power scales faster with the number of atoms than in the case of standard Dicke superradiance. Moreover, we study the coherence properties of the burst and observe a sharp transition between two regimes: in the first, the phase coherence between the atoms is seeded by the excitation laser. In the second, it is seeded by vacuum fluctuations. Our results shed light on the collective radiative dynamics of spatially extended ensembles of quantum emitters and may turn out useful for generating multi-photon Fock states as a resource for quantum technologies.

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Quantum simulation with Rydberg states of erbium atoms

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Lanthanide atoms provide a rich platform for a number of ultracold atom experiments due to their variety of available optical transitions, strong anisotropic interactions and the large spin space of their fermionic ground states [1]. Leveraging these properties alongside established methods for creating large, programmable and defect-free arrays of single atoms in optical tweezers [2,3] promises to provide an exciting system for quantum simulation.

We present our progress in implementing a quantum simulator utilising Rydberg states of erbium trapped in an optical tweezer array. We have already identified approximately 550 states in the erbium Rydberg series including a possible state from the *g*-series to which excitation is only possible due to the incompletely filled erbium *f*-shell [4]. Recently, we started loading atoms in our array of traps and expect to find a large range of erbium Rydberg states enabled by their positive polarisability. In the future, the large 7/2 nuclear spin of the fermionic ^{167}Er isotope may allow us to implement computational schemes involving up to 8-level qudit states.

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Fermionic matter-wave quantum optics with cold-atom impurity models

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When quantum emitters (i.e. few-level quantum systems) are coupled to a dissipative environment, this coupling induces spontaneous decay and gives rise to bath-mediated interactions between the emitters. Structuring the bath, i.e. engineering non-trivial spectral properties, can lead to additional exotic phenomena, such as population trapping in bound states, non-exponential decay, purely coherent long-range interactions, sub- and superradiant collective emission, and more. It has been recently suggested [1,2] and experimentally demonstrated [3] that cold bosonic atoms in state-dependent optical lattices can be used to realise matter-wave analogues of traditional waveguide QED setups, thus offering a new platform for exploring such phenomena. We propose an extension of these cold-atom setups to fermionic atoms, which unlocks a new scenario in the study of quantum emitters in structured baths: quantum optics with *fermionic* matter waves. We discuss how the theoretical formalism capturing single-excitation dynamics in atom-photon systems can be adapted to the study of multi-excitation dynamics in simple fermionic impurity models. Within this new framework, we present signatures of non-Markovian individual and collective dynamics, as well as intriguing ground-state features, and, in doing so, establish some connections between well-established results from the fields of quantum optics and condensed matter physics.

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Chiral quantum-optical elements and waveguide-QED with sub-wavelength Rydberg-atom arrays

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We propose a novel approach to achieve unprecedentedly strong photon-photon interaction and subsequently chiral manipulation of photonic quantum states based on a two-dimensional Rydberg array driven around two-photon Raman resonance in the Autler-Townes regime. We find that a completely blockaded 2D Rydberg array is equivalent to a single spatially-extended ``giant atom'' losslessly coupled to a paraxial probe field with arbitrary spatial profile, leading to perfect anticorrelation between the reflected probe photons. Combination of this ``giant atom'' with linear optical elements can mimic the chiral coupling between a two-level atom and the probe photons with nearly perfect coupling efficiency (~0.9993), which further enables remarkably high-fidelity photon sorter (~0.9998) in an almost deterministic manner.