Symposium Quantum Cooperativity of Light and Matter (SYQC)

jointly organised by
the Quantum Optics and Photonics Division (Q),
the Atomic Physics Division (A), and
the Molecular Physics Division (MO)

Joachim von Zanthier
Friedrich-Alexander-Universität Erlangen-Nürnberg
Staudtstraße 1
91058 Erlangen
joachim.vonzanthier@fau.de

Kai Phillip Schmidt
Friedrich-Alexander-Universität Erlangen-Nürnberg
Staudtstraße 7
91058 Erlangen
kai.phillip.schmidt@fau.de

Ferdinand Schmidt-Kaler
Johannes Gutenberg-Universität Mainz
Staudingerweg 7
55128 Mainz
fsk@uni-mainz.de

Giovanna Morigi
Universität des Saarlandes
Campus E2.6
66123 Saarbrücken
giovanna.morigi@physik.uni-saarland.de

Cooperative behavior is ubiquitous in nature. It can be understood as the enhanced response of a system of many particles with respect to isolated entities such that the ensemble behaves differently than a single unit. In the quantum domain the collective response is brought about by some mutual coupling among the particles establishing non-local and long-range quantum correlations in space and time. Quantum collective behavior induced by the buildup of quantum spatio-temporal correlations in mesoscopic light-matter systems is the topic of the Symposium Quantum Cooperativity of Light and Matter. The symposium brings together leading scientists with expertise in theoretical and experimental quantum optics and condensed-matter physics to investigate a wide variety of experiments and platforms.

Overview of Invited Talks and Sessions

(Lecture hall Audimax)

Invited Talks

SYQC 1.1	Thu	10:30–11:00	Audimax	**Super- and subradiant states of an ensemble of cold atoms coupled to a nanophotonic waveguide** — •Arno Rauschenbeutel
SYQC 1.6	Thu	12:00–12:30	Audimax	**Cooperative Effects in Pigment-Protein Complexes: Vibronic Renormalisation of System Parameters in Complex Vibrational Environments** — •Susana F. Huelga
SYQC 2.1	Thu	14:00–14:30	Audimax	**Quantum simulation with coherent engineering of synthetic dimensions** — •Paola Cappellaro
SYQC 2.6	Thu	15:30–16:00	Audimax	**Quantum Fractals** — •Cristiane Morais-Smith

Sessions

SYQC 1.1–1.6	Thu	10:30–12:30	Audimax	**Quantum Cooperativity of Light and Matter - Session 1**
SYQC 2.1–2.6	Thu	14:00–16:00	Audimax	**Quantum Cooperativity of Light and Matter - Session 2**
SYQC 3.1–3.8	Fri	10:30–12:30	Q-H15	**Quantum Cooperativity (joint session Q/SYQC)**

SYQC 1: Quantum Cooperativity of Light and Matter - Session 1

Time: Thursday 10:30–12:30 Location: Audimax

Invited Talk SYQC 1.1 Thu 10:30 Audimax

Super- and subradiant states of an ensemble of cold atoms coupled to a nanophotonic waveguide — •Arno Rauschenbeutel — Department of Physics, Humboldt-Universität zu Berlin, Germany

We experimentally and theoretically investigate collective radiative effects in an ensemble of cold atoms coupled to a single-mode optical nanofiber. Our analysis unveils the microscopic (i.e., atom per atom) dynamics of the system, showing that collective interactions gradually build up along the atomic ensemble in the direction of propagation of the nanofiber-guided excitation light pulses. Our theoretical results are supported by time-resolved measurements of the light transmitted and reflected by the atomic ensemble. In particular, when the excitation pulse is switched off on a time scale much shorter than the atomic lifetime, a superradiant decay up to 17 times faster than the single-atom decay rate is observed in the forward direction, while no speed-up occurs in the backward direction. For longer time scales, our measurements reveal the evolution of the ensemble from the superradiant state to a set of states that are fully subradiant with respect to the nanofiber-guided mode. Notably, our theoretical model identifies this complex dynamics as a key feature of the time evolution of one-dimensional systems prepared in a timed Dicke state. Our results highlight the unique opportunities offered by nanophotonic cold-atom systems for the experimental investigation of collective light-matter interaction.

SYQC 1.2 Thu 11:00 Audimax

Cooperative effects in dense cold atomic gases including magnetic dipole interactions — •Nico Bassler[1,2], Marvin Proske[3], Ishan Varma[3], Niels Petersen[3,4], Patrick Windpassinger[3,4], Kai Phillip Schmidt[1], and Claudiu Genes[2] — [1]Department of Physics, Friedrich-Alexander-Universität (FAU) Erlangen Nürnberg — [2]Max-Planck-Institut für die Physik des Lichts, Erlangen — [3]QUANTUM, Institut für Physik, JGU Mainz — [4]Graduate School Materials Science in Mainz

We theoretically investigate cooperative effects in cold atomic gases exhibiting both electric and magnetic dipole-dipole interactions, such as occurring in Dysprosium gases. In the quantum non-degenerate case, a quantum optics path is taken to show the emergence of tailorable XXZ quantum spin models in the high excitation limit. In the opposite case of the low excitation limit, we aim to provide analytical and numerical results detailing the effect of magnetic interactions on the directionality of scattered light and characterize sub- and superradiant effects. In the quantum degenerate case, we consider a many body physics approach in order to show the interplay between sub- and superradiance and the fermionic or bosonic quantum statistics of the gas.

SYQC 1.3 Thu 11:15 Audimax

Collective photon emission patterns from two atoms in free space — •Stefan Richter[1], Sebastian Wolf[2], Joachim von Zanthier[1], and Ferdinand Schmidt-Kaler[2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, Staudtstraße 1, 91058 Erlangen — [2]QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Modification of spontaneous decay in space and time is a central topic of quantum physics. It has been predominantly investigated in cavity quantum electrodynamic systems. However, altered spontaneous decay may equally result from correlations among the emitters in free space, as observed in super- and subradiance. Yet, such projective preparation of an entangled quantum state and the resulting modified emission pattern has not been observed due to the lack of ultra-fast multi-pixelated cameras. Using two trapped ions in free space, we projectively prepare atoms and observe the corresponding collective photon emission. Depending on the direction of detection of the first photon, we record fundamentally different emission patterns, including super- and subradiance. Our results demonstrate that the detection of a single photon may fundamentally determine the subsequent collective emission pattern of an atomic array, here represented by its most elementary building block of two atoms.

SYQC 1.4 Thu 11:30 Audimax

Modified spontaneous emission rates in free space via conditional measurements — •Manuel Bojer[1], Lukas Götzendörfer[1], Romain Bachelard[2], and Joachim von Zanthier[1] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — [2]Departamento de Física, Universidade Federal de São Carlos, Rodovia Washington Luís, km 235 - SP-310, 13565-905 São Carlos, SP, Brazil

We study the emission properties of three identical two-level atoms initially prepared in the excited state by measuring Glauber's third-order intensity correlation function. Assuming two of the three atoms located close to each other, such that they are subject to the dipole-dipole interaction, while the third one is placed several wavelengths away, we observe super- or subradiant emission behavior for the last recorded photon. Differently from the case where no conditional measurements are performed and/or no remote atom is present, the emission pattern presents both spatial and temporal modifications. In fact, the first two conditional photon measurements associated with the three-photon correlation function entangle the remote atom with the two other atoms while the dipole-dipole interaction between the two close atoms allows manipulating the decay rates, leading to a rich interference pattern for the last recorded photon with effective symmetric and antisymmetric decay rates depending on the direction of observation.

SYQC 1.5 Thu 11:45 Audimax

Coulomb interactions in pulsed laser-triggered electron beams from tungsten needle tips — •Stefan Meier, Jonas Heimerl, and Peter Hommelhoff — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Tungsten needle tips represent well-suited electron sources for various applications, including electron diffraction, electron microscopy or electron holography. In cold field emission, these tips provide a highly coherent electron beam, with coherence being the key parameter for most electron-optical applications. When femtosecond laser pulses are focused on the tip, electrons can be emitted promptly, leading to an ultrafast pulsed electron source. Previously, we could show that femtosecond pulsed electron emission is spatially as coherent as cold field emission from the same tip when operated with currents well below one electron per pulse on average [1]. In this talk, we show that the spatial coherence decreases when more than one electron per pulse is emitted on average, starting already at below one electron per pulse. These results are quantitatively well supported by numerical point-particle simulation results. Last, we show that the coherence decrease can be interpreted as an effective source size growth [2]. We will conclude with an outlook on the current status of correlation measurements, which might allow us to enter the quantum correlation regime and might, ultimately, yield quantum limited electron beams.

[1] S. Meier *et al.*, Appl. Phys. Lett. **113**, 143101 (2018).
[2] S. Meier and P. Hommelhoff, manuscript submitted.

Invited Talk SYQC 1.6 Thu 12:00 Audimax

Cooperative Effects in Pigment-Protein Complexes: Vibronic Renormalisation of System Parameters in Complex Vibrational Environments — •Susana F. Huelga — Institute of Theoretical Physics and IQST, Ulm University, Germany

The primary steps of photosynthesis rely on the generation, transport and trapping of excitons in pigment-protein complexes (PPCs). Generically, PPCs possess highly structured vibrational spectra, combining many discrete intra-pigment modes and a quasi-continuous of protein modes, with vibrational and electronic couplings of comparable strength. The intricacy of the resulting vibronic dynamics poses significant challenges in establishing a quantitative connection between spectroscopic data and underlying microscopic models. By considering two model systems, namely the water-soluble chlorophyll-binding protein of cauliflower and the special pair of bacterial reaction centers, we show how to address this challenge using numerically exact simulation methods. We demonstrate that the inclusion of the full multi-mode vibronic dynamics in numerical calculations of linear optical spectra lead to systematic and quantitatively significant corrections to electronic parameter estimation. These multi-mode vibronic effects are shown to be relevant in the longstanding discussion regarding the origin of long-lived oscillations in multidimensional nonlinear spectra.

SYQC 2: Quantum Cooperativity of Light and Matter - Session 2

Time: Thursday 14:00–16:00 Location: Audimax

Invited Talk SYQC 2.1 Thu 14:00 Audimax

Quantum simulation with coherent engineering of synthetic dimensions — •Paola Cappellaro — Nuclear Science and Engineering Department, Massachusetts Institute of Technology (MIT), Cambridge, USA

The high controllability of engineered qubit systems can be leveraged to explore exotic condensed matter systems by simulating synthetic topological phases of matters. Observation of novel effects can be achieved even in small quantum systems by exploiting their periodic driving, which can mimic the properties of spatially periodic materials and elucidate their symmetry and topological features. Two challenges have so-far prevented such exploration, the lack of an experimentally accessible characterization protocol and of strong-enough driving fields. Here I'll show how to overcome both challenges to achieve the first experimental study of dynamical symmetries and the observation of symmetry-protected selection rules * and their breaking. I will further show how these methods can be used to synthesize and characterize a tensor monopole in the 4D parameter space described by the spin degrees of freedom of a single solid-state defect in diamond. These results demonstrate the power of coherent control and Floquet engineering for quantum simulation.

SYQC 2.2 Thu 14:30 Audimax

Excitonic tonks-girardeau and charge-density wave phases in monolayer semiconductors — •Rafał Ołdziejewski[1,2], Alessio Chiocchetta[3], Johannes Knörzer[1,2], and Richard Schmidt[1,2] — [1]Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany — [3]Institute for Theoretical Physics, University of Cologne, Zülpicher Strasse 77, 50937 Cologne, Germany

Excitons in two-dimensional semiconductors provide a novel platform for fundamental studies of many-body interactions. In particular, dipolar interactions between spatially indirect excitons may give rise to strongly correlated phases of matter that so far have been out of reach of experiments. Here, we show that excitonic few-body systems in atomically thin transition-metal dichalcogenides confined to a one-dimensional geometry undergo a crossover from a Tonks-Girardeau to a charge-density-wave regime. To this end, we take into account realistic system parameters and predict the effective exciton-exciton interaction potential. We find that the pair correlation function contains key signatures of the many-body crossover already at small exciton numbers and show that photoluminescence spectra provide readily accessible experimental fingerprints of these strongly correlated quantum many-body states.

SYQC 2.3 Thu 14:45 Audimax

Propagation of ultrashort pulses in resonant X-ray waveguides — •Petar Andrejić[1], Leon Merten Lohse[2,3], and Adriana Pálffy[1] — [1]Friedrich-Alexander Universität Erlangen-Nürnberg — [2]Deutsches Elektronen-Synchrotron — [3]Georg-August-Universität Göttingen

Thin film structures are a well established and powerful platform for coupling and control of X-rays with resonant Mössbauer nuclei. Existing formalisms describe well the collective nuclear response in grazing incidence experiments, including for inhomogeneous hyperfine splittings [1], however, these formalisms assume long duration, well collimated synchrotron pulses, such that the problem can be considered quasi-monochromatic, with uniform amplitude.

Here, we show that ultrashort X-ray pulses coupled into to a thin film waveguide can propagate as guided modes over millimetre scale distances. The guided wave spectrum and spatial profiles are obtainable using the existing Green's function formalism. The coupling of the guided modes to the resonant nuclei embedded within the waveguide leads to a set of first order, few-mode Maxwell-Bloch equations, from which we obtain the transmission spectra of the waveguide. We discuss the properties of these spectra, including the role of the resonant nuclei in coupling otherwise orthogonal guided modes to each other, as well as the connection with the super-radiance decay and the collective Lamb shift previously observed in grazing incidence.

[1] P. Andrejić and A. Pálffy, Phys. Rev. A 104, 033702 (2021)

SYQC 2.4 Thu 15:00 Audimax

A systematic study of entanglement mediated by a thermal reservoir. — •Sayan Roy, Christian Otto, Raphaël Menu, and Giovanna Morigi — Theoretical Physics, Department of Physics, Saarland University, 66123 Saarbrücken, Germany

Entanglement is the main reason that allows quantum protocols to surpass the classical ones [1]. However, because of its quantum nature, it gets destroyed due to decoherence processes that occur as a result of interaction of the system with its surrounding environment [2]. Here, we investigate a model where environment-induced entanglement is observed. We consider two non-interacting defect spins coupled to a common thermal reservoir, modeled by a spin-$\frac{1}{2}$ Ising chain in a transverse field. Hereby, each of the defect spins is coupled to only one spin of the chain. We analyze the time evolution of the density matrix of the two defect spins which are initially prepared in a separable state. We identify three different regimes characterizing the dynamics of quantum correlations, which depend on the strength of the coupling between defect spins and spin chain. We discuss several scenarios by varying the distance and coupling strength between the two spins and provide physical insights into the dynamics.

[1] R. Horodecki, M. Horodecki and K. Horodecki Rev. Mod. Phys. **81(2)**, 865-942 (2009).
[2] W.H. Zurek Rev. Mod. Phys. **75(3)**, 715-775, (2003).

SYQC 2.5 Thu 15:15 Audimax

Applying continuous unitary transformations to open quantum systems — •Lea Lenke, Matthias Mühlhauser, and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

We generalize the method of continuous unitary transformations (CUTs) to certain types of open systems. In some cases – such as gain-loss Hamiltonians – there exists an effective description in terms of non-Hermitian Hamiltonians. For the latter we successfully apply a perturbative CUT (pCUT) to two non-Hermitian PT-symmetric quantum spin models in order to determine their low-energy physics [1]. In a next step, we aim at generalizing this method further to dissipative frustrated systems described by a Lindblad master equation.

[1] L. Lenke, M. Mühlhauser, and K. P. Schmidt, "High-order series expansion of non-Hermitian quantum spin models", Phys. Rev. B 104, 195137 (2021).

Invited Talk SYQC 2.6 Thu 15:30 Audimax

Quantum Fractals — •Cristiane Morais-Smith — Institute for Theoretical Physics, University of Utrecht, The Netherlands

The human fascination for fractals dates back to the time of Christ, when structures known nowadays as a Sierpinski gasket were used in decorative art in churches. Nonetheless, it was only in the last century that mathematicians faced the difficult task of classifying these structures. In the 80's and 90's, the foundational work of Mandelbrot triggered enormous activity in the field. The focus was on understanding how a particle diffuses in a fractal structure. However, those were **classical fractals**. This century, the task is to understand **quantum fractals**. In 2019, in collaboration with experimental colleagues from the Debye Institute, we realized a Sierpinski gasket using a scanning tunneling microscope to pattern adsorbates on top of Cu(111) and showed that the wavefunction describing electrons in a Sierpinski gasket fractal has the Hausdorff dimension d = 1.58 [1,2]. However, STM techniques can only describe **equilibrium** properties. Now, we went a step beyond and using state-of-the-art photonics experiments in collaboration with colleagues at Jiao-Tong University in Shanghai, we unveiled the **quantum dynamics** in fractals. By injecting photons in waveguide arrays arranged in a fractal shape, we were able to follow their motion and understand their quantum dynamics with unprecedented detail. We built and investigated 3 types of fractal structures to reveal not only the influence of different Hausdorff dimension, but also of geometry [3].

[1] S.N. Kempkes, M.R. Slot, S.E. Freeney, S.J.M. Zevenhuizen, D. Vanmaekelbergh, I. Swart, and C. Morais Smith, *Design and characterization of electronic fractals*, Nature Physics **15**, 127 (2019).
[2] Physics Today **72**, 1, 14 (2019) https://physicstoday.scitation.org/doi/full/10.1063/PT.3.4105

[3] X.-Y. Xu, X.-W. Wang, D.-Y. Chen, C. Morais Smith, and X.-M. Jin, *Shining light on quantum transport in fractal networks*, Nature Photonics **15**, 703 (2021).

SYQC 3: Quantum Cooperativity (joint session Q/SYQC)

Time: Friday 10:30–12:30 Location: Q-H15

SYQC 3.1 Fri 10:30 Q-H15

Interplay of periodic dynamics and noise: insights from a simple adaptive system — •Frederic Folz[1], Kurt Mehlhorn[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Algorithms and Complexity Group, Max-Planck-Institut für Informatik, Saarland Informatics Campus, 66123 Saarbrücken, Germany

We study the dynamics of a simple adaptive system in the presence of noise and periodic damping. The system is composed by two paths connecting a source and a sink, the dynamics is governed by equations that usually describe food search of the paradigmatic Physarum polycephalum. In this work we assume that the two paths undergo damping whose relative strength is periodically modulated in time and analyse the dynamics in the presence of stochastic forces simulating Gaussian noise. We identify different responses depending on the modulation frequency and on the noise amplitude. At frequencies smaller than the mean dissipation rate, the system tends to switch to the path which minimizes dissipation. Synchronous switching occurs at an optimal noise amplitude which depends on the modulation frequency. This behaviour disappears at larger frequencies, where the dynamics can be described by the time averaged equations. Here, we find metastable patterns that exhibit the features of noise-induced resonances.

SYQC 3.2 Fri 10:45 Q-H15

A software pipeline for simulating and evaluating incoherent diffraction imaging — •Sebastian Karl[1], Stefan Richter[1], Fabian Trost[2], Henry Chapman[2], Ralf Röhlsberger[3], and Joachim von Zanthier[1] — [1]University of Erlangen-Nuremberg, Staudtstr. 1, 91058 Erlangen — [2]Center for Free-Electron Laser Science, Notkestraße 85, 22607 Hamburg — [3]Helmholtz-Institute Jena, Max-Wien-Platz 1, 07743 Jena

Conventional x-ray crystallography relies on coherent scattering for high resolution structure determination. However often the predominant scattering mechanism is an incoherent process like fluorescence, introducing severe background in the coherent diffractogram. Incoherent diffractive imaging (IDI) aims to use this incoherently scattered light for structure determination by measuring second order correlations n the far field [1]. While in theory single shot 3d imaging would be possible using IDI, careful theoretical examinations place thresholds on its feasibility in both the high [2] and low [3] photon limit. We present a software pipeline facilitating simulation and evaluation of IDI images of structures ranging from crystals to mircometer-size masks. Since this pipeline is able to account for mode mixing identified as the main obstacle in [3], it enables realistic estimations of necessary photon fluxes and image shot numbers for IDI experiments.

[1] A. Classen et al, PRL 119, 053401, 2017
[2] F. Trost et al., New J. Phys. 22, 083070, 2020
[3] L. M. Lohse, Acta Cryst. A 77, 480-496, 2021

SYQC 3.3 Fri 11:00 Q-H15

Twisted matter waves and reference frame motions. — •Alexey Okulov — Russian Academy of Sciences, 119991, Moscow, Russia

When superfluid is loaded in helical trap the external disturbances affect translational and rotational dynamics in nontrivial way. The conventional approach is to consider reference frame transformations corresponding to translations, rotations and linear accelerations. In mean-field Gross-Pitaevskii equation with a weakly modulated linear velocity, rotation and free-fall acceleration it is possible to obtain exact solutions which connect linear displacements of reference frame $\vec{V}$ to rotations of atomic ensemble and vise versa rotations of reference frame $\vec{\Omega}_{\oplus}$ are the cause of linear displacements of ensemble. Linear accelerations being equivalent to gravitational force induce phase modulation of macroscopic wavefunction.

SYQC 3.4 Fri 11:15 Q-H15

Quantum criticality of the long-transverse-field Ising model extracted by Quantum Monte Carlo simulations — •Jan Alexander Koziol, Anja Langheld, Sebastian C. Kapfer, and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

The quantum criticality of the ferromagnetic transverse-field Ising model with algebraically decaying interactions is investigated by means of stochastic series expansion quantum Monte Carlo, on both the one-dimensional linear chain and the two-dimensional square lattice. Utilizing finite-size scaling (FSS), we extract the full set of critical exponents as a function of the decay exponents of the long-range interactions. We resolve the three different regimes predicted by field theory, ranging from the nearest-neighbor Ising to the long-range Gaussian universality classes with an intermediate regime giving rise to a continuum of critical exponents. Focusing on the non-trivial intermediate regime, we verify our study by the well-known limiting regimes. In the long-range Gaussian regime, we treat the effect of dangerous irrelevant variables on the homogeneity laws by means of a modern FSS formalism.

SYQC 3.5 Fri 11:30 Q-H15

Measuring the temperature of laser-cooled ions via resonance fluorescence — •Marvin Gajewski[1], Giovanna Morigi[1], Walther Hahn[2,3], Sebastian Wolf[4], Wenbing Li[2,4], Christoph Düllmann[2,4,5], Dmitry Budker[2,4,6], and Fedinand Schmidt-Kaler[4,2] — [1]Saarland University, Saarbrücken, Germany — [2]Helmholtz-Institut, Mainz, Germany — [3]IQOQI, Innsbruck, Austria — [4]Johannes Gutenberg-Universität, Mainz, Germany — [5]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — [6]University of California, Berkeley, USA

The fluorescence light emitted by atoms and ions carries information about their mechanical motion. We show how the temperature of an ion crystal could be inferred from the resonance fluorescence: By means of a theoretical formalism we identify the optimal conditions on saturation and detuning at which this thermometry is most efficient. We then argue that this theory is not only relevant for experimental identification of intruder ions traversing or captured in a large ion crystal, but also for investigating the heat capacity of such mesoscopic systems.

SYQC 3.6 Fri 11:45 Q-H15

Finite-Size Scaling at Quantum Phase Transitions Above the Upper Critical Dimension — •Anja Langheld, Jan Alexander Koziol, Patrick Adelhardt, Sebastian C. Kapfer, and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

We present a modern formalism for finite-size scaling (FSS) at quantum phase transitions (QPT) above the upper critical dimension. The upper critical dimension becomes experimentally accessible, for instance, in systems with long-range interactions such as the long-range transverse-field Ising model, which can be realized in systems of trapped ions. In general, FSS at phase transitions above the upper critical dimension requires a special treatment as dangerous irrelevant variables (DIV) lead to modifications in the homogeneity laws, thereby causing the breakdown of hyperscaling and standard FSS. Following the recently developed Q-FSS formalism addressing this issue for thermal phase transitions, we transfer the idea to QPT while stressing the subtle differences and connections to the classical version. By relaxing the long-standing belief that the correlation length is unaffected by DIV, the presented FSS formalism fixes the aforementioned issues above the upper critical dimension and recovers a generalized hyperscaling relation. The influence of DIV on the correlation length is explicitly confirmed using numerical calculations of the long-range transverse-field Ising model.

SYQC 3.7 Fri 12:00 Q-H15

Cavity-induced long-range interactions in strongly correlated

systems — •Paul Fadler[1], Jiajun Li[2], Kai Phillip Schmidt[1], and Martin Eckstein[1] — [1]Friedrich-Alexander Universität Erlangen-Nürnberg — [2]Paul Scherrer Institut

In recent years, the coupling of optical cavity modes to solid states systems has emerged as a possible way to control material properties. Here we investigate cavity-induced long-range interactions between spins in a Mott insulator, which are a new feature of the coupling to the quantized cavity field and are absent in the control of magnetism by classical light. In detail, we show that coupling a cavity mode to the Fermi-Hubbard model at half filling leads to long-range four-spin terms in the effective low spin model at large onsite-interaction U, in addition to the conventional local antiferromagnetic Heisenberg exchange interaction. To obtain these long-range interactions, we compare exact diagonalization, a perturbative approach based on the effective spin-photon Hamiltonian description of the system, and fourth-order perturbation theory in the Hubbard model. We show that knowing the phenomenologically determined spin-photon matrix elements is not sufficient to derive the photon-mediated spin-interactions; instead, long-range interactions are additionally mediated via virtual intermediate states, that involve multiple excitations in the charge sector. A similar point should be kept in mind for deriving photon-mediated long-range interactions between emergent low-energy degrees of freedom in interacting systems in general.

SYQC 3.8 Fri 12:15 Q-H15

Quantum Criticality of the long-range antiferromagnetic Heisenberg ladder — •Patrick Adelhardt and Kai Phillip Schmidt — FAU Erlangen-Nürnberg, Germany

The Mermin-Wagner theorem excludes the breaking of a continuous symmetry in one-dimensional spin systems at zero temperature for sufficiently short-ranged interactions. Introducing algebraically decaying long-range couplings on the antiferromagnetic Heisenberg two-leg ladder, we show that a direct second-order quantum phase transition between the topologically ordered rung-singlet phase in the short-range limit and a conventionally Néel-ordered antiferromagnet can be realized in a one-dimensional system. We study the quantum-critical breakdown in the rung-singlet phase using the method of perturbative continuous unitary transformations (pCUT) on white graphs in combination with classical Monte Carlo simulations for the graph embedding in the thermodynamic limit supplemented with linear spin-wave calculations and exact diagonalization to extract the critical point. Exploiting (hyper-)scaling relations, the pCUT method is used to determine the entire set of canonical critical exponents as a function of the decay exponent. We find that the critical behavior can be divided into a long-range mean-field regime and a regime of continuously-varying exponents similar to the long-range transverse-field Ising model despite the presence of distinct orders on different sides of the critical point and the absence of criticality in the short-range limit.