Q 18: Quantum Optics: Cavity and Waveguide QED I

Time: Tuesday 11:00–13:00 Location: E214

Invited Talk Q 18.1 Tue 11:00 E214

Atoms coupled to nanofibers: from topological phases to correlated photon emission — •Beatriz Olmos — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — The University of Nottingham, Nottingham, NG7 2RD, United Kingdom

An ensemble of emitters coupled to a common environment displays collective behaviour. This includes the enhanced and inhibited emission of photons from the ensemble (so-called super and subradiance, respectively), and the emergence of induced dipole-dipole interactions among the emitters. Among these structures, so-called nanophotonic waveguides such as single mode optical nanofibers particularly stand out, since the translationally invariant nature of the nanofiber-guided modes gives rise to infinitely ranged couplings between the emitters. In this talk, I will summarize some of the latest theoretical results in my group, where we have shown how these all-to-all interactions can facilitate the study of non-trivial topology, the emergence of phase transitions, and correlated photon emission, among other phenomena.

Q 18.2 Tue 11:30 E214

Effective mode theory for open quantum systems — •Lucas Weitzel Dutra Souto, Felix Riesterer, Dominik Lentrodt, and Andreas Buchleitner — University of Freiburg, Germany

In the frequently employed theoretical approaches for open resonator QED systems, one usually considers a quantum emitter - such as an atom - in a cavity which interacts with a few discrete electromagnetic cavity modes. Losses and leakage from the cavity are modelled via a (weak) interaction with the environment. Models that employ this treatment, as is the case for the seminal Jaynes-Cummings model and its generalizations, have been tremendously successful in describing experiments. However, these models are intrinsically phenomenological and it is not known if they hold in all situations, as the underlying approximations are still unclear. For instance, in the case of strongly leaking systems, such as plasmonic cavities, this approach is not valid anymore and various theoretical assumptions need to be reassessed. We hence try to answer the following question: Is it possible to construct from first principles a few-mode description for leaky cavities in the spirit of the Jaynes-Cummings model? This will extend our theoretical understanding of more general systems or, in the case of a negative answer, lead to a no-go theorem.

Q 18.3 Tue 11:45 E214

Crafting the dynamical structure of synchronization by harnessing bosonic multi-level cavity QED — •Riccardo J. Valencia-Tortora[1], Shane P. Kelly[1], Tobias Donner[2], Giovanna Morigi[3], Rosario Fazio[4,5], and Jamir Marino[1] — [1]JGU Mainz, Mainz, Germany — [2]ETH Zürich, Zürich, Switzerland — [3]Saarland University, Saarbrücken, Germany — [4]ICTP, Trieste, Italy — [5]Università di Napoli Federico II, Napoli, Italy

Recently, the theoretical and experimental investigation of multi-level cavity systems has gathered increasing attention. Yet, the rich diversity of dynamical responses they can host is still widely unexplored, and the few individual results call for a unifying picture both for theoretical and experimental purposes. We present a framework which could serve this scope based on a dynamical reduction hypothesis, which in summary states that the dynamics of collective observables can be described by a few-body effective Hamiltonian. Using this conjecture as a guiding principle, we intuitively explain and craft the dynamical response of an exchange model for SU(N) spins mediated by cavity photons after a quench. In this regard, we unveil the susceptibility of the dynamical response of multi-level systems to quantum fluctuations and intra-levels entanglement, observing among the others the onset of a chaotic phase characterized by exponential sensitivity to the initial conditions. To conclude, we discuss possible extensions to other spin-exchange quantum simulators and a universal conjecture for the dynamical reduction of non-integrable all-to-all interacting systems.

Q 18.4 Tue 12:00 E214

Cascaded photon emission of a single three-level ladder atom into two cavities — •Gianvito Chiarella, Tobias Frank, Pau Farrera, and Gerhard Rempe — Max Planck Institute for Quantum Optics, Garching bei München, Germany

Crossed Fiber Cavities coupled to single 87Rb atoms have proven to be a potentially useful resource for quantum communication applications [1,2]. Their main feature lies in the capability to couple two distinct light modes to two atomic transitions simultaneously with high cooperativity. This property makes them a good candidate for the investigation of fundamental phenomena in quantum optics which manifest in the presence of two vacuum fields strongly interacting with the atom. We explore the scenario where the cavities couple to two electrical-dipole transitions of a three-level ladder atom. In certain parameters regimes, we predict an effect for which the atom relaxes down the ladder states into its ground state emitting two resonant photons without populating the intermediate state. In this talk, I will present the theoretical simulation of such a model and discuss its experimental implementation.

Q 18.5 Tue 12:15 E214

Light-matter interaction at the transition between cavity and waveguide QED — •Daniel Lechner, Riccardo Pennetta, Martin Blaha, Philipp Schneeweiss, Jürgen Volz, and Arno Rauschenbeutel — Humboldt Universität zu Berlin, Institut für Physik, Newtonstr. 15, 12489 Berlin

The interaction between a light field and an ensemble of quantum emitters is usually described in the framework of cavity quantum electrodynamics (QED) or waveguide QED. The choice depends on whether the emitters interact with a single-mode light field confined in a resonator or a propagating one, for which a continuum of frequency modes is allowed. These two branches of quantum optics share the common goal of harnessing light-matter coupling. However, they often use very different experimental set-ups and theoretical descriptions. Here, we experimentally and theoretically explore the transition from cavity to waveguide QED with an ensemble of cold atoms that is coupled to a fiber-ring resonator containing a nanofiber section. By changing the length of the resonator from a few meters up to several tens of meters, we tailor the spectral density of modes of the resonator without affecting the system's cooperativity parameter. We demonstrate that for progressively longer resonators, the paradigmatic Rabi oscillations of cavity QED gradually vanish while signatures of the dynamics typical for waveguide QED appear.

Q 18.6 Tue 12:30 E214

Relativistic formulation of quantum electrodynamical density functional theory for cavities — •Valeriia Kosheleva[1], Lukas Konecny[1], Heiko Appel[1], Angel Rubio[1,2], and Michael Ruggenthaler[1] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Center for Free Electron Laser Science, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Center for Computational Quantum Physics (CCQ), The Flatiron Institute, 162 Fifth Avenue, New York, New York 10010, USA

Recent advances in cavity QED, particularly in polaritonic chemistry, necessitate the development of theoretical methods for describing many-electron systems strongly coupled to photons. One of the most popular ab initio approaches for modeling realistic materials is density functional theory (DFT). Recently, this theory was generalized for cavity systems [1,2] and is referred as quantum electrodynamical density functional theory (QEDFT). The matter part in QEDFT is usually treated within non-relativistic formalism which is a good approximation for light element-containing systems. However, as soon as heavier atoms are involved relativistic effects become essential for understanding the physical and chemical properties of atoms and molecules. In the present work, we introduce relativistic reformulation of cavity QEDFT. As an example, we consider the application of our formalism to study the the effect of strong coupling on absorption spectra of molecules containing heavy atoms.

[1] I. V. Tokatly, Phys. Rev. Lett. 110, 233001 (2013).
[2] M. Ruggenthaler et al., Phys. Rev. A 90, 012508 (2014).

Q 18.7 Tue 12:45 E214

Quantum Theory for Self-organization in Many-body Cavity QED — •Tom Schmit[1], Simon Jäger[2], Tobias Donner[3], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany — [3]Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland

Ensembles of atoms strongly coupled with the electric field of an optical cavity offer a formidable laboratory for studying the out-of-equilibrium dynamics of long-range systems in the quantum regime. In this work, we derive by means of the formalism developed in Ref. [1] a quantum master equation describing the dynamics of atoms which interact with a multimode high-finesse cavity. We then derive the BBGKY hierarchy and analyse the predictions in several relevant limits. Our theory reproduces the results of the experiment of Ref. [2] and provides a powerful tool for singling out the individual contributions to the onset of metastability in quantum globally-interacting systems.

[1] S. B. Jäger, T. Schmit, G. Morigi, M. J. Holland, and R. Betzholz, Phys. Rev. Lett. **129**, 063601 (2022).
[2] A. Morales, P. Zupancic, J. Léonard, T. Esslinger, and T. Donner, Nature Materials **17**, 686 - 690 (2018).