Q 5: Collective Effects and Disordered Systems

Time: Monday 11:00–13:00 Location: HS I PI

Q 5.1 Mon 11:00 HS I PI

Non-Linear Maser Oscillations at Room Temperature — •Christoph W. Zollitsch[1,2], Christopher W. M. Kay[1,3], and Jonathan D. Breeze[2] — [1]Department of Chemistry, Saarland University, Saarbrücken, Germany — [2]Department of Physics & Astronomy, University College London, London, UK — [3]London Centre for Nanotechnology, University College London, London, UK

The recent realization of a continuous-wave room temperature maser, using NV^- centers in diamond pumped by a 532 nm laser, is a promising platform for novel research and development in areas of signal amplification, timekeeping and sensing. Typically, for such applications a maser oscillator is operated in linear response regime. For masing, the NV^- spin ensemble is pumped into a non-equilibrium state and, for strong enough pump rates, can also be driven into a non-linear regime. Maser oscillation changes dramatically, exhibiting a frequency-comb like spectrum, instead of a single narrow frequency mode. Studying nonlinear behavior in room temperature solid-state masers can lead to new pathways of quantum sensing.

We present an NV^- center maser system and experimentally characterize the transition from linear to non-linear maser oscillation, via frequency and time domain analysis. A feature for non-linear behavior is bifurcation. Here, the inhomogeneous broadened spin distribution experiences bifurcation. The dynamics can be modelled numerically through a quantum master equation with Lindbladian dissipators and is in excellent agreement with experimental data. We discuss individual features of non-linear dynamics and their potential applications.

Q 5.2 Mon 11:15 HS I PI

Melting of Devil's staircases in the long-range Dicke-Ising model — •Jan Alexander Koziol and Kai Phillip Schmidt — Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstraße 7, 91058 Erlangen, Germany

We present ground-state phase diagrams of the antiferromagnetic long-range Ising model under a linear coupling to a single bosonic mode on the square and triangular lattice. In the limit of zero coupling the ground state magnetization forms a Devil's staircase structure of magnetization plateaux as a function of an applied longitudinal field in Ising direction. The linear coupling to a single bosonic mode melts this structure to a so-called superradiant phase with a finite photon density in the ground state. The long-range interactions lead to a plethora of intermediate phases that break the translational symmetry of the lattice, as well as having a finite photon density. To study the ground-state phase diagram we apply an adaption of the unit-cell-based mean-field calculations [1,2], which capture all possible magnetic unit cells up to a chosen extent. Further, we exploit a mapping of the non-superradiant phases to the Dicke model in order to calculate upper bounds for phase transitions towards superradiant phases [3]. In the case of second-order phase transitions, these bounds agree with the boundaries determined by the mean-field calculations.

[1] J. A. Koziol et al., SciPost Phys. 14, 136 (2023)
[2] J. A. Koziol et al., SciPost Phys. 17, 111 (2024)
[3] A. Schellenberger et al., SciPost Phys. Core 7, 038 (2024)

Q 5.3 Mon 11:30 HS I PI

Exploiting emergent symmetries in disorder-averaged dynamics — •Mirco Erpelding[1], Adrian Braemer[2], and Martin Gärttner[1] — [1]Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany — [2]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Symmetries are a key tool in understanding quantum systems and, among many other things, allow efficient numerical simulation of dynamics. Disordered systems usually feature reduced sym- metries and additionally require averaging over many realizations, making their numerical study computationally demanding. However, when studying quantities linear in the time evolved state, i.e. expectation values of observables, one can apply the averaging procedure to the time evolution operator resulting in an effective dynamical map, which restores symmetry on the level of super- operators. In this work, we develop schemes for efficiently constructing symmetric sectors of the disorder-averaged dynamical map using short-time and weak-disorder expansions. To benchmark the method, we apply it to an Ising model with random all-to-all interactions in the presence of a transverse field. After disorder averaging, this system becomes effectively permutation invariant, and thus the size of the symmetric subspace scales polynomially in the number of spins allowing for the simulation of very large systems.

Q 5.4 Mon 11:45 HS I PI

Cooperative Quantum Dynamics based on Solid State Quantum Emitters — •Lukas Strauch[1], Stefan Nimmrichter[2], and Mario Agio[1,3] — [1]Laboratory of Nano-Optics, University of Siegen, 57072 Siegen, Germany — [2]TQO, Universität Siegen, Deutschland — [3]National Institute of Optics (INO), National Research Council (CNR), 50125 Florence, Italy

The investigation of the collective radiative dynamics of ring ordered subwavelength spaced point-like dipole emitters and their coupling is crucial for the development of quantum devices, which mimics artificial light harvesting complexes. The coherent and incoherent coupling determines the collective quantum dynamics. Here, we study the effect of decoherence on the cooperative emission dynamics of the complexes, paving a way towards experimental implementation based on solid-state quantum emitters coupled to resonant nanostructures.

Q 5.5 Mon 12:00 HS I PI

Analytical model for the description of the collective nonlinear response of large ensembles of two-level emitters — Max Schemmer, Martin Cordier, Lucas Pache, Philipp Schneeweiss, •Jürgen Volz, and Arno Rauschenbeutel — Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin

The nonlinear interaction between light and ensembles of quantum emitters is the key ingredient for the generation of non-classical states of light and a central focus of current experimental and theoretical research. Here, we present a model that allows one to theoretically describe and investigate the collective nonlinear optical response of an ensemble of two-level emitters that are weakly coupled to a single-mode waveguide [1]. Our approach generalizes the insight that photon-photon correlations in the light scattered by a single two-level emitter result from two-photon interference to the case of many emitters, where a collective enhancement of the two-photon emission can take place. Using this model, we study different configurations and derive analytical expressions for the second-order correlation function as well as for the squeezing spectrum of the output light. Our results agree with predictions from more computationally expensive models, and show how the collectively enhanced nonlinear response of weakly coupled emitters can be harnessed to generate non-classical states of light using ensembles of thousands of emitters.

[1] M. Schemmer et al., arXiv:2410.21202 (2024)

Q 5.6 Mon 12:15 HS I PI

Dipole-dipole interactions of strongly driven two-level atoms — •Tim Ehret, Vyacheslav Shatokhin, and Andreas Buchleitner — Hermann-Herder-Str. 3, Institute of Physics, Albert-Ludwigs University of Freiburg

We formulate a Floquet-Markov master equation for two spatially separated atoms driven by an intense electromagnetic field and coupled to a common bath. This equation features a modified form of dipolar interactions as compared to the case of weakly driven atoms, giving rise to new shifts in the Floquet quasienergy spectrum of the system. We provide a detailed physical interpretation of the modified dipole-dipole interactions, discuss their manifestations in two-atom resonance fluorescence, and extract the distance-dependence of the dipole force between the atoms.

Q 5.7 Mon 12:30 HS I PI

Examination of the antiferromagnetic superradiant intermediate phase and the effects of geometrical frustration in the Dicke-Ising Model — •Jonas Leibig — Chair for Theoretical Physics V, FAU Erlangen-Nürnberg, Germany

We map the Dicke-Ising model to a self-consistent matter Hamiltonian in the thermodynamic limit [1, 2] and solve it using a variety of methods, including exact diagonalization, perturbative and numerical linked-cluster expansions, and density matrix renormalization group. In one dimension, we explore the intermediate phase in the antiferromagnetic model and the multi-critical point in the ferromagnetic model, comparing our results with complementary quantum Monte Carlo simulations [2]. Additionally, we investigate the antiferromagnetic model on the frustrated geometry of the sawtooth chain. We employ high-order series expansions in the strong coupling limit, where the mapping to the self-consistent matter Hamiltonian is definitively valid. Independently, we analyze in greater detail whether the mapping also holds in the specific regime emerging from the frustrated Ising limit induced by an infinitesimal light-matter perturbation.

[1] K. Lenk, J. Li, P. Werner, and M. Eckstein, "Collective theory for an interacting solid in a single-mode cavity", *arXiv preprint arXiv:2205.05559*, 2022.
[2] A. Langheld, M. Hörmann, and K. P. Schmidt, "Quantum phase diagrams of Dicke-Ising models by a wormhole algorithm", *arXiv preprint arXiv:2409.15082*, 2024.

Q 5.8 Mon 12:45 HS I PI

Disorder-dependent phases of optically deep atomic ensembles — •Kasper J. Kusmierek[1], Max Schemmer[2], Sahand Mahmoodian[3], and Klemens Hammerer[1] — [1]ITP, Leibniz University Hannover, Germany — [2]Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (CNR-INO), Fiorentino, Italy — [3]Centre for Engineered Quantum Systems, University of Sydney, Australian

The interaction of light with an ensemble of two-level systems in a one-dimensional geometry is commonly described by two key models of quantum electrodynamics (QED): the driven-dissipative Dicke model or the Maxwell-Bloch equations. Both exhibit distinct features of phase transitions and separations, depending on optical depth and drive strength. Using a parent spin model derived from bidirectional waveguide QED, we show these models arise as limits corresponding to small and large disorder in atomic positions. We numerically solve the mean-field equations and investigate the phase diagram depending on optical depth, drive strength, and disorder. For the unidirectional model we go beyond mean-field theory by performing a second-order cumulant expansion, complementing analytical mean-field results. Studying atomic inversion and light transmission, we find, in the thermodynamic limit, phase separation occurs with a critical value dependent on the degree of order but not on inhomogeneous broadening effects. Even far from the thermodynamic limit, this critical value marks a special point in the atomic correlation landscape of the unidirectional model. We conclude disordered effective one-dimensional systems can be modeled using unidirectional waveguide approaches.