DAΛLI Workshop

Delving into LIGHT-MATTER INTERACTIONS and their APPLICATIONS

12-14 October 2022

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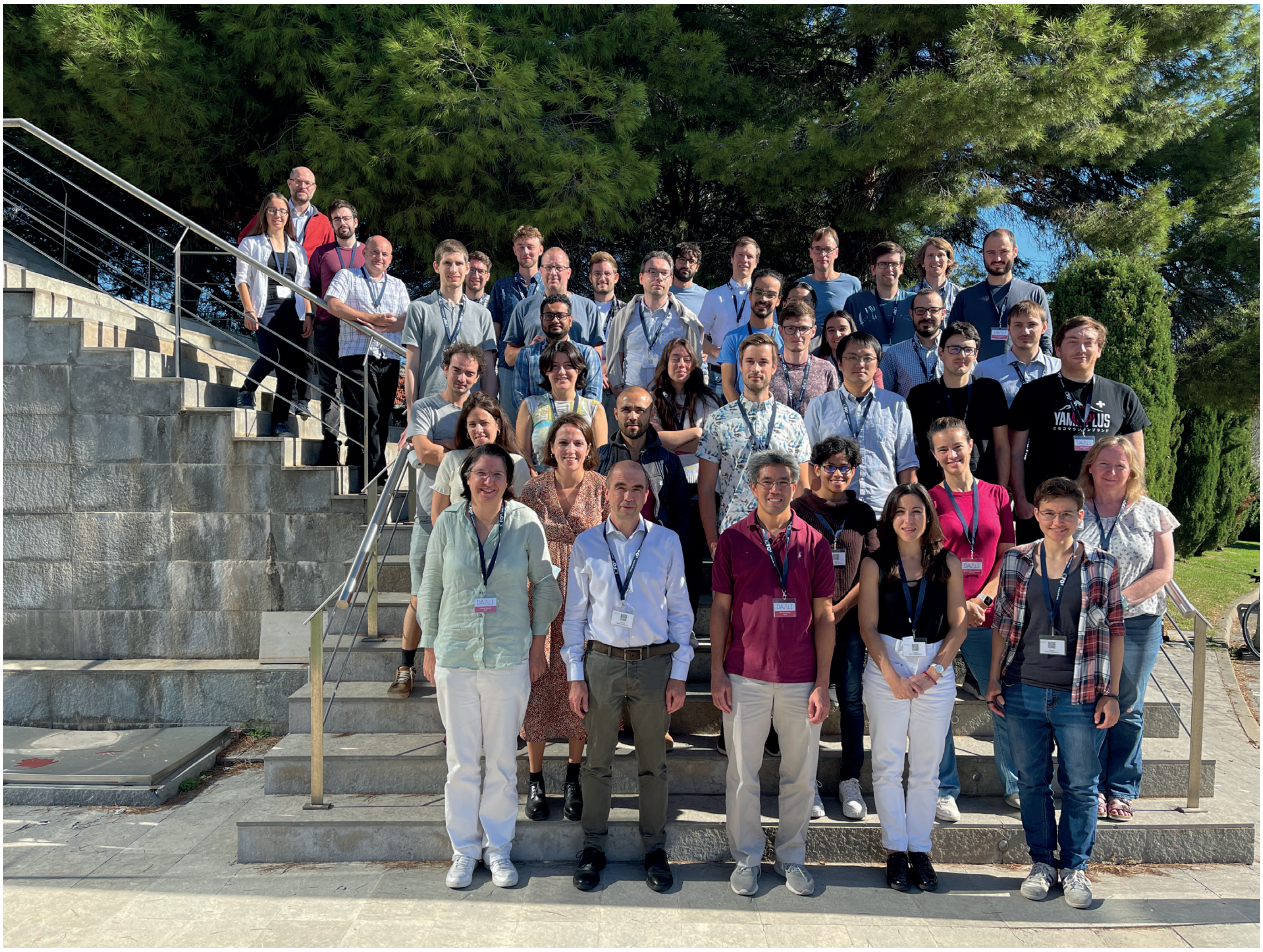
Introduction

The interaction between photons and atoms is the basis for a wide range of applications such as quantum memories for light and nonlinear optics at the single-photon level. Despite many spectacular demonstrations of atom-light interactions, current interfaces still face major limitations.

From October 12-14, 2022, the DAALI team is offering a workshop aimed at gathering experts in atomic physics, quantum optics and photonics, both theoretical and experimental, to discuss the current status and progress of the field and delve into novel approaches, techniques and methods to understand, observe and be able to control and manipulate atom-photon interactions.



Programme

Wednesday, October 12th		
16:00-15:15	Welcome	
16:15-17:00	Programmable interactions and entanglement engineering between atomic ensembles	Phillipp Kunkel (Standford University)
17:00-17:45	Nanophotonic cavity QED with cold atoms	Chen-Lung Hung (Purdue University)
17:45-18:15	Coffee Break	
18:15-18:45	Talk by Barak Dayan	Barak Dayan (Weizmann Institute)
18:45-19:15	Interfacing a highly non-linear Rydberg medium with a quantum memory for quantum networks	Jan Lowinski (ICFO)

Venue & Date

Venue: Gran Hotel Rey Don Jaime, Castelldefels (Barcelona)
Dates: 12,13 & 14 October 2022

Thursday, October 13th

10:00-10:45	Switching an atomically thin mirror with a single Rydberg atom	Johannes Zeiher (Marx-Plank Institute of Quantum Optics)
10:45-11:30	Topological waveguide QED simulators	Alejandro González-Tudela (Instituto de Física Fundamental, CSIC)
11:30-12:00	Coffee Break	
12:00-12:45	Making hot atoms interact	Robert Löw (Universität Stuttgart)
12:45-13:15	Light scattering by two-level emitters revisited	Jürgen Volz (Vienna Center for Quantum Science and Technology)
13:15-17:00	Lunch, free discussion & ICFO Labs tour	
17:00-17:45	Many-body QED with atoms and photons	Kyung Choi (University of Waterloo)
17:45-18:30	Using optical nanofibres to mediate cold atom interactions	Sile Nic Chormaic (Okinawa Institute of Science and Technology)
18:30-19:00	Controlling single-photon reflection from waveguide-coupled atomic array	Tridib Ray (Okinawa Institute of Science and Technology)

Friday, October 14th

10:00-10:45	Subradiant edge states in an atom chain with waveguide-mediated hopping	Beatriz Olmos Sánchez (Universität Tübingen)
10:45-11:30	Quantum nonlinear optics and multi-emitter experiments with quantum dots in waveguide	Peter Lodahl (University of Copenhagen)
11:30-12:00	Coffee Break	
12:00-12:45	Observation of non-equilibrium superradiant phase transition in free space	Giovanni Ferioli (Institut d'Optique, CNRS)
12:45-13:15	The driven dissipative superradiant phase transition	Lisa Bombieri (ICFO)
13:15-17:00	Lunch & free discussion	
17:00-17:45	Integrable rare-earth material platforms for quantum techonologies	Diana Serrano (Chimie Paristech, CNRS)
17:45-18:30	Many-body superradiance in atomic arrays	Ana Asenjo (Columbia University)
18:30-19:00	Building subwavelength arrays with atomic strontium	Toni Rubio (ICFO)

Programmable interactions and entanglement engineering between atomic ensembles

Philipp Kunkel

Interactions form the basis for the experimental generation of entanglement between quantum objects. Using all-to-all interactions, numerous experiments with atomic ensembles have generated quantum states which provide a higher precision in sensing protocols compared to unentangled states. However, many envisioned applications in quantum sensing and computation require greater control over the spatial entanglement structure and, thus, the effective graph of interactions. In our experiment, we use an optical cavity together with local spin rotations to mediate programmable long-range interactions within a 1D array of atomic ensembles. Driving the cavity with light induces all-to-all interactions between the spin-1 atoms, creating atom pairs and quantum correlations within a single spatially extended mode of the collective transversal spin. In this case, we measure spin-nematic squeezing and verify the generation of entanglement between spatially separated ensembles by quantifying the correlations in two non-commuting observables. By employing local spin rotations, we selectively couple different spatial modes to the cavity and thus control the structure of the generated quantum correlations. This capability allows for tailoring the entanglement structure to a specific quantum enhanced task such as distributed quantum sensing and measurement-based quantum computation.

Nanophotonic cavity QED with cold atoms

Chen-Lung Hung

Integration of cold neutral atoms with nanoscale photonics has become a new paradigm as a light-matter interface in the settings of cavity and waveguide QED. New opportunities are enabled by recent advances in nanophotonic engineering, as well as cooling and trapping single to an array of atoms near nanoscale dielectrics to realize scalable and efficient atom-light interactions. In this talk, I will discuss our recent progress in nanophotonic cavity QED by coupling single atoms to a microring resonator fabricated on a planar nanophotonic optical circuit. We observe efficient chiral atom-photon coupling to a whispering gallery mode and nonclassical on-chip photons routed by a stream of optically funneled cold atoms. Our approach combines precision optical guiding, created by near-field diffracted light on a nanophotonic waveguide, and evanescent field potential to achieve controlled atom localization. I will discuss prospects of multi-atom array trapping for nanophotonic cavity QED. Our realization paves a way towards new applications utilizing trapped atoms on a nanophotonic circuit for quantum optics and many-body physics.

Interfacing a highly non-linear Rydberg medium with a quantum memory for quantum networks

Jan Lowinsky

Switching an atomically thin mirror with a single Rydberg atom
Johannes Zeiher

Ordered arrays of emitters with subwavelength spacing have emerged as a novel platform to realize light-matter interfaces. The strong light-matter coupling down to the level of single photons is rooted in the cooperative optical response of the entire array. In our experiment, we realize such an ordered atomic array by preparing a near-unity filled Mott insulator in an optical lattice deep in the atomic limit. We confirm the cooperative nature of the array by probing the subradiant optical response both in reflection and transmission of a weak laser beam. Employing strong dipolar Rydberg interactions, we subsequently controllably switch the optical properties of the entire array with a locally addressed single ancilla atom. Driving Rabi oscillations on the ancilla, we demonstrate coherent control of transmission and reflection of the mirror. Our results pave the way towards the realization of novel quantum metasurfaces with spatial mode control and the creation of controlled atom-photon entanglement.

Topological waveguide QED simulators
Alejandro Gonzalez Tudela

In this talk I will review a recent series of works in which emitters interact with topological waveguides [1-5], and explain what kind of new single and many-body phenomena emerges, as well as their potential applications as analog quantum simulators.

[1] Science advances 5 (7), eaaw0297 (2019)
[2] Physical Review A 104 (5), 053522 (2021)
[3] Physical Review X 11 (1), 011015 (2021)
[4] PRX Quantum 3 (1), 010336 (2022)
[5] arXiv:2207.02090

Making hot atoms interact
Robert Löw

The research and the spectroscopy of hot vapors carries great potential, ranging from fundamental research to robust applications in the context of quantum technologies.

In the past decades the spectroscopy of atomic and molecular gases at room temperature has lost some attention due to the focus on cold atomic systems. Still, due to their experimental simplicity, their robustness, and their fundamental nature, they hold the promise to realize real-world quantum devices. Their narrow-band transitions and high optical depths enable such vapor cell science to implement excellent sensors, references, metrologic devices or building blocks in quantum optics.

In this talk I will focus on optical non-linearities induced by atom-atom interactions, either by highly excited Rydberg states or for low lying states via the resonant dipole-dipole interaction. These non-linearities are manifest at the single photon level and can be exploited to generate and process non-linear light fields. As a platform we us a variety of cell types and excitation schemes, where the most advanced ones involve integrated photonic waveguides and microresonators.

Light scattering by two-level emitters revisited
Jürgen Volz

Many-body QED with atoms and photons
Kyung Choi

Understanding and creating novel forms of light-matter quantum systems stimulates a broad and fundamental insights in quantum science. Remarkably, complex physical processes can arise as an emergent phenomena from an interacting network of light and matter. In this talk, I will introduce a class of strong-coupling quantum optics, where coherent atom-cavity dynamics is intertwined with the internal gauge constraints imposed on the quantum material. I will discuss the conceptual paradigm of many-body quantum electrodynamics (QED) for which novel quantum phases can be stabilized for a Rydberg ice when reactively coupled to the QED vacuum of the cavity. I will discuss the recent laboratory observation of a plethora of quantum phases in the reactive limit of many-body QED, including the detection of cavity spin liquid states that belong to different superselection charge sectors. Cavity QED toolboxes enable novel quantum probes, including the dynamical response functions of quasiparticles in the spin liquids and their quantum statistics. Moving beyond the reactive limit, highly-entangled states may be born entirely from quantum fluctuations at scale and genuinely “surprising” behaviour of light and matter may emerge from the dynamical frustration between global strong-coupling and local many-body constraints.

Using optical nanofibers to mediate cold atom interactions
Sile Nic Chormaic

Optical nanofibres – very thin, tapered optical fibres 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 fibre-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 nanofibres to manipulate, trap, and control cold 87Rb 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 nanofibre field and introduce some of the limitations observed.

Controlling single-photon reflection from a waveguide-coupled atomic array
Tridib Ray

Subradiant edge states in an atom chain with waveguide-mediated hopping
Beatriz Olmos Sanchez

We analyze the topological and dynamical properties of a system formed by two chains of identical emitters coupled to a waveguide, whose guided modes induce all-to-all excitation hopping. We find that, in the single excitation limit, the bulk topological properties of the Hamiltonian that describes the coherent dynamics of the system are identical to the ones of a one-dimensional Su-Schrieffer-Heeger (SSH) model. However, due to the long-range character of the exchange interactions, we find weakening of the bulk-boundary correspondence. This is illustrated by the variation of the localization length and mass gap of the edge states encountered as we vary the lattice constant and offset between the chains. Most interestingly, we analytically identify parameter regimes where edge states arise which are fully localized to the boundaries of the chain, independently of the system size. These edge states are shown to be not only robust against positional disorder of the atoms in the chain, but also subradiant, i.e., dynamically stable even in the presence of inevitable dissipation processes, establishing the capacity of waveguide QED systems for the realization of symmetry protected topological phases.

Quantum nonlinear optics and multi-emitter experiments with quantum dots in waveguide
Peter Lodahl

I will review recent experimental progress on quantum emitters deterministically interfaced to light in nanophotonic waveguides. Experimental results on the dynamical nonlinear response and the collective coupling between multiple emitters will be presented, in addition to potential applications for photon sorting and photonic quantum gates.

Observation of a non-equilibrium superradiant phase transition in free space
Giovanni Ferioli

We observe a non-equilibrium phase transition in a driven dissipative quantum system consisting of a pencil shape cloud of laser-cooled Rb atoms in free space, optically excited along its main axis [1]. By measuring the excited state population dynamics and the light emitted in the superradiant mode, we find that our data are well reproduced by the iconic Driven Dicke model [2,3], simply using an effective atom number. We characterize steady-state properties of the system, observing the characteristic ..2
scaling of the photon emission rate in the superradiant phase. Finally, we observe a modification of the statistics of the superradiant light as we cross the phase transition.

[1] Ferioli, G., et al. “Observation of a non-equilibrium superradiant phase transition in free space.” arXiv preprint arXiv:2207.10361 (2022).
[2] Agarwal, G. S., et al. “Collective atomic effects in resonance fluorescence.” Physical Review A 15.4 (1977): 1613.
[3] Walls, D. F., et al. “Non-equilibrium phase transitions in cooperative atomic systems.” Progress of Theoretical Physics Supplement 64 (1978): 307-320.

The driven dissipative superradiant phase transition – cavity QED vs. free space

Lisa Bombieri

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. 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 propose a quasi-1D “chiral waveguide” model as a minimal model for free space. We find that it exhibits exactly the same mathematical structure as the cavity Dicke model, except for an extra contribution of coherent “dipole-dipole” interactions that physically encodes pulse propagation effects. 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.

Integrable rare-earth material platforms for quantum technologies

Diana Serrano

The use of rare-earth ions to build quantum light-matter interfaces relies on nano-fabricating crystalline host materials preserving the narrow optical and spin linewidths of rare-earth emitters while enabling integration into nanophotonic devices. This has led to the research and development of alternative rare-earth material platforms as nanoparticles, thin films, and more recently, rare-earth molecular crystals. Here we review some of these platforms and report promising results obtained with Y2O3:Eu3+ nanoparticles and Eu3+ molecular crystals, including ultra-narrow linewidths and optical storage proof-of-principle demonstrations.

Many-body superradiance in atomic arrays

Ana Asenjo

Dissipation and fluctuations are known to be sources of order in complex non-linear systems formed by many agents, as they lead to self-organized spatial or temporal structures. Here, I will discuss how coherent behavior emerges in large quantum systems consisting of many atoms if dissipation is collective, in the form of correlated photon emission and absorption. In particular, I will discuss the many-body out-of-equilibrium physics of atomic arrays coupled to baths of different dimensionality. I will focus on the problem of Dicke superradiance, where a collection of excited atoms synchronizes as they decay, emitting a short and intense pulse of light. Superradiance remains an open problem in extended systems due to the exponential growth of complexity with atom number. I will show that superradiance is a universal phenomenon in ordered arrays. Our predictions can be tested in state of the art experiments with arrays of neutral atoms, molecules, and solid-state emitters and pave the way towards understanding the role of many-body decay in quantum simulation, metrology, and lasing.

Building subwavelength arrays with atomic strontium

Toni Rubio

The development of novel light-matter platforms can play a key role for many applications of quantum science. Atomic arrays, made up of individual atoms arranged either in optical lattices or tweezers, display novel features emerging from cooperative light-matter interactions. In particular, strongly subradiant modes appear in subwavelength arrays, enabling the storage of light for long times. Furthermore, 2D arrays can act as nearly perfect mirrors for resonant photons, making them efficient light-matter platforms.

The goal of our lab at ICFO, within the DAALI project, is to realize a defect-free 2D atomic array based on ultracold bosonic strontium. As is the case for other alkaline-earth elements, strontium displays many desirable optical features, such as narrow and ultranarrow transitions. Additionally, the well-established magic-wavelength dipole traps can be used to avoid resonance broadening and reduce the heating of the system during optical probing of the array. In this talk I will describe the design of our experiment, summarize its current status and detail the next steps ahead.