CoScaLi 2016

Workshop on Collective Scattering of Light

Ubatuba – SP, Brazil

May 9-12, 2016
CoScaLi 2016

The role of coherences between atomic dipoles has gained an ever increasing importance with the advent of ultracold atoms and large trapped ion systems: Classical and quantum correlations between particles can be created and manipulated, with important consequences for the study of fundamental properties of matter and for quantum information.

This workshop addresses the collective properties of light scattering in these many-body systems, at the frontier between the microscopic and macroscopic realms. The coupling between light and an ensemble of classical or quantum scatterers, and the induced correlations, will be intensively discussed.

The main topics are the following:

- Cooperative scattering
- Anderson localization of light
- Dicke super and subradiance
- Mesoscopic physics with cold atoms
- Multiple scattering of light
- Ab initio models for light scattering
Program

Sergey Skipetrov – Localization of light in a cloud of cold atoms in magnetic field ........................................ 1
Igor M. Sokolov – Light trapping and localization in a cold and dense atomic ensemble located in magneto-static field ................................................................. 2
Carlos E. Maximo – Spatial and temporal localization of light in two dimensions ........................................ 3
Gordon Robb – Optomechanical Self-Structuring in Cold Atomic Gases ..................................................... 4
François Damanet – Collective spontaneous emission with quantized atomic motion ................................ 5
Joachim von Zanthier – Dicke superradiance and Hanbury Brown and Twiss intensity interference: two sides of the same coin ......................................................... 6
Arturo Lezama – Fluctuations in light after traversing an atomic sample .................................................... 8
Felipe Pinheiro – Probing scattering resonances of Vogel’s spirals with the Green’s matrix spectral method ..... 9
Paulo Hisao Moryia – Coherent backscattering of inelastic photons from single atoms and their mirror images .. 10
Marios C. Tsatsos – Beyond mean-field investigations of Bose-Einstein condensates: principles and applications in ultracold atomic gases ............................................. 11
Daniel Felinto – Resonant interaction of a broadband single photon with a dense atomic ensemble .......... 12
Robin Kaiser – Dicke Sub- and Superradiance .................. 13
Tiago José Arruda – Tuning the electromagnetic wave transport in two-dimensional disordered media containing gyrotropic core-shell cylinders ........................................ 14
Monika Ritsch – Attractive Optical Forces from Blackbody Radiation ........................................ 15
Nicolas Cherroret – From multiple scattering to van der Waals interactions and vice versa ............... 16
Paulo Americo Maia Neto – Probing the Casimir force with optical tweezers ............................ 17
Sebastian Slama – Cooperative coupling of ultracold atoms and surface plasmons ....................... 18
Michelle Araújo – Superradiance in a large cloud of cold atoms in the linear optics-regime .............. 19
Pablo Saldanha – Single-photon superradiance in a quantum memory ........................................ 20
Nicola Piovella – Nonlinear effects in the cooperative scattering by cold atoms .......................... 21
Thierry de Silans – Redistribution of light frequency by multiple scattering in a resonant atomic vapor 22
Patrícia Castilho – Cooperative two-photon absorption in a BEC of sodium atoms ....................... 23
Sandra Vianna – Cooperative frequency shift in three-photon resonant four-wave mixing ............... 24
Philippe Courteille – Gravimetry with in vivo monitoring of matter waves ................................... 25
Marina Samoylova – Quantum Enhanced Interferometry .......................................................... 26
Helmut Ritsch – Spontaneous crystallization of light and ultracold atoms in free space ................. 27
François Impens – Recoherence from non-locality ................................................................. 29
Analabha Roy – Simulation of Quantum Spin Dynamics by Phase Space Sampling of BBGKY Trajectories 30
Johannes Schachenmayer – Collective atomic emission and its interplay with motional effects in dense clouds of Sr atoms ................................................................. 31
Robert Bettles – Cooperativity in lattice monolayers of driven interacting dipoles ....................... 32
Natalia R. de Melo – Intrinsic Optical Bistability in a Rydberg ensemble ..................................... 33
Localization of light in a cloud of cold atoms in magnetic field

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We have recently shown that multiple scattering of light in a random three-dimensional ensemble of cold atoms cannot lead to the appearance of localized states, contrary to scattering of electrons on impurities in a solid-state sample [1]. This is due to the opening of a new energy transport channel by the dipole-dipole interactions between nearby atoms [2], and was later confirmed by an independent study [3]. We find, however, that localized states can be induced by an external magnetic field that partially suppresses the dipole-dipole interactions [4]. Several questions then arise: is the resulting localization transition experimentally observable? Should it be considered Anderson transition (as many other localization-delocalization transitions taking place in disordered systems)? And in which universality class should it be classified? After giving a quick review of our work on the topic of light localization, we will report on the recent progress that we made in attempt to answer these questions.

We study theoretically the influence of static magnetic field on light trapping and localization in a cold and dense atomic ensemble prepared in an atomic trap. The analysis is based on the consistent quantum-posed theoretical approach developed previously in [1]. In the framework of this approach we solve the nonstationary Schrodinger equation for the wave function of the joint system consisting of N motionless atoms and a weak electromagnetic field. Restriction of the total number of states taken into account allows us to find approximately the wave function of the system and consequently to analyze both the properties of atomic system and the light. Our study shows that static magnetic field essentially modifies resonant dipole-dipole interatomic interaction. This effect influences strongly on light trapping. We found out appearance of long lived polyatomic collective states which lifetimes essentially exceed those take place in the absence of magnetic field. Calculation of inverse participation ration shows that these states are localized. Scaling analysis of collective eigenstates distribution revealed that, in many aspects, this distribution exhibits the behavior expected for the Anderson transition driven by disorder. On the basis of our approach we analyze also the possibility to observe manifestation of these long-lived localized states in experiment. We study the dynamics of fluorescence of atomic clouds initiated by pulse radiation. In the presence of magnetostatic field radiation trapping time increases considerably. We analyze as well the influence of magnetic field on the steady-state transmission of plain layer of motionless atomic scatterers.

Multiple scattering of waves has been the subject of intense debates in the context of disorder-induced Anderson localization. Nevertheless, despite several decades of research, the mere existence of Anderson localization of light in the prominent case of three dimensions (3D) remains debated [1-2]. On the other hand, two-dimensional (2D) experiments have reported Anderson localization of light for scattering of scalar waves. However, the vector nature of light may be crucial in case of point scatterers [1]. For this reason we have focused our efforts on a 2D vector model of scattering [3]. Our theoretical model predicts a reduced dimensionality by geometrical constraints which brings out to the existence two regimes of scattering: one corresponding to a scalar model of light and the other one corresponding to a vectorial model of light. Hence we are able to do a direct comparison between the presence or the absence of polarization degrees of freedom and the presence or the absence of near field terms interactions, making it an ideal tool to investigate the role of polarization in light localization phenomena. Performing a scaling analysis we observe in both cases long lived atomic modes of the scattering, yet only the scalar case exhibits Anderson localized modes. Investigating the reasons for the absence of localization in cold atoms ensambles, it appears that both the coupling of polarization and the presence of near field terms are able to prevent long lifetimes and Anderson localization. We finally show that, albeit modes with extremely long lifetimes are present only in the localization regime, surprisingly these lifetimes and their localization length are uncorrelated.

The interaction between light and cold atomic gases can give rise to nonlinear, self-structuring instabilities which involve spontaneous formation of optical and atomic density patterns. Features of these instabilities in both thermal and degenerate gases will be described.
We derive and solve a markovian master equation for the internal dynamics of an ensemble of indistinguishable two-level atoms including all effects related to the quantization of their motion [1]. Our equation provides a unifying picture of the consequences of recoil and indistinguishability of atoms beyond the Lamb-Dicke regime on both their dissipative and conservative internal dynamics, and is relevant for experiments with ultracold atoms. We give general expressions for the decay rates and the dipole-dipole shifts for any motional states, and we find analytical formulas for a number of relevant states (Gaussian states, Fock states and thermal states). We show that dipole-dipole interactions and cooperative spontaneous emission can be modulated through the motional state of atoms. As an application, we study the impact of the quantized atomic motion on Dicke super- and subradiance [2]. In particular, we compute the radiated energy rate up to 30 atoms and provide analytical predictions for large number of atoms based on a mean-field approach [3,4].

Superradiance is one of the outstanding problems in quantum optics since Dicke introduced the concept of spontaneous emission of coherent radiation by an ensemble of two-level atoms in highly entangled Dicke states [1]. The startling gist is that even though the atoms have no dipole moment they radiate with increased intensity in particular directions. While a substantial amount of literature has been published on this topic [2-6], the physical origin of the phenomenon remained largely obscure. A deeper understanding has emerged recently in terms of quantum interferences among multiple path ways produced by systems in correlated states [7]. Based on this interpretation we investigate a new aspect of superradiance, namely that it can be observed also with independent initially uncorrelated sources. In our approach the production of correlation among the sources and subsequent superradiant emission relies on the successive measurement of photons at particular positions, such that the detection process is unable to identify the individual photon sources. In this case, the initially fully excited system cascades down the ladder of symmetric Dicke states each time a photon is recorded [8,9]. Detecting m photons scattered from $N > m$ atoms amounts to measuring the m-th order photon correlation function. Measuring this function allows (a) to produce any desired symmetric Dicke state from initially uncorrelated sources and (b) to observe the corresponding superradiant behavior of the resultant Dicke state. As it turns out the same approach is also applicable for initially uncorrelated classical sources [8]. The setup used to display the superradiant emission characteristics of initially uncorrelated sources is similar to the one employed in the Hanbury Brown and Twiss experiment. The detailed analysis shows that the two effects derive indeed from the same cause, namely from multi-photon interferences appearing in the m-th order photon correlation function. In this way it is shown that Hanbury Brown and Twiss intensity interference and Dicke superradiance are two sides of the same coin.


Fluctuations in light after traversing an atomic sample

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The interaction of light with a homogeneous sample of atoms has been used as a fundamental test bench for nonlinear and quantum optics. While the simplest models only consider the coupling of light with a two-level atomic system, several important effects are due to the internal atomic structure, namely the Zeeman degeneracy of the atomic energy levels. We review the role of the Zeeman degeneracy in nonlinear effects such as electromagnetically induced transparency and absorption and consider the effect of the Zeeman degeneracy on the fluctuations of the light field traversing the atomic sample. We discuss the fundamental difference between two-level and multi-level atomic systems and describe recent experiments in which atom-light interaction results in quadrature and polarization squeezing as well as two-mode entanglement.
Using the rigorous Green’s function spectral method [1,2], we systematically investigate the scattering resonances of different types of Vogel [3] spiral arrays of point-like scatterers. By computing the distributions of eigenvalues of the Green’s matrix and the corresponding eigenvectors we obtain important physical information on the spatial nature of the optical modes, their lifetimes and spatial patterns, at small computational cost and for large-scale systems [4]. We emphasize the unique properties of aperiodic Vogel spirals with respect to random scattering media, which have been investigated so far. Finally, we show that this method can be extended to the study of 3D Vogel aperiodic metamaterials and aperiodic photonic structures that may exhibit a richer spectrum of localized resonances of direct relevance to the engineering of novel optical light sources and sensing devices.

Coherent backscattering of inelastic photons from single atoms and their mirror images

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Coherent Back Scattering (CBS) is a coherence effect in the propagation of waves through disordered media involving two or more scatterers. This effect is understood as a constructive interference between photons scattered by two time-reversed paths, leading to an enhanced scattering into the backward direction [1,2]. Unfortunately, several effects can lead to a loss of coherence and consequently to a reduction in the CBS contrast, such as the presence internal structure in the scatterers, saturation and media density. By using a simple trick, the coherence effects on the back scattered light can be recovered in optically thin samples: the introduction of a dielectric mirror. In this scheme, there will be constructive interference between light scattered by the original atom and its image, eventually resulting in a CBS process [3]. Here we referred this effect as mirror-assisted Coherent Back-Scattering (mCBS) which has been observed for classical scatterers [4]. In this talk, I will present the observation of the mCBS from a sample of laser cooled Strontium atoms and a dielectric mirror. Due to the robustness of the mCBS to dephasing induced by strong saturation, I will present the contribution of inelastic photons to the interference process.

Beyond mean-field investigations of Bose-Einstein condensates: principles and applications in ultracold atomic gases

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Bose-Einstein condensation, theoretically known to appear at ultralow temperatures since the 1920s, was achieved in the laboratory only 20 years ago, in dilute bosonic gases at temperatures close to absolute zero. The wide range of applications and controllability of the system parameters has made them unprecedented tools for exploring novel quantum phases and behavior. The most common theoretical method employed to tackle these complex systems, typically consisting of tens of thousands of interacting particles is the celebrated mean-field Gross-Pitaevskii model. Even though it has been proven successful in describing various types of nonlinear excitations it does not take into consideration fragmentation and correlations that can develop in time. I will briefly present a systematic theory, the MultiConfigurational Time-Dependent Hartree for Bosons (MCTDHB) [1] that has been developed in order to solve the many-body Schroedinger equation beyond the mean-field approach and can be in principle exact, and the latest numerical implementation (solver) that is freely distributed in the web [2]. I will then discuss some particular applications in Bose gases possessing angular momentum and interacting vortices and discuss the novel concept of phantom vortices. The latter are topological defects in rotating gases that evade detection in the density of the gas but give their signature in the correlation function. Last I will present recent theoretical and experimental investigations in nearly-1D gases where periodic modulation of the scattering length might give rise to granulated states and beyond-mean-field phenomena.

Resonant interaction of a broadband single photon with a dense atomic ensemble

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The interaction of an ensemble of atoms with common vacuum modes may lead to an enhanced emission into these modes. This phenomenon, known as superradiance, highlights the coherent nature of spontaneous emission, resulting in macroscopic entangled states in mundane situations. The complexity of the typical observations of superradiance, however, masks its quantum nature, allowing alternative classical interpretations. Here we stress how this picture changed with the implementation ten years ago of a new process for single-photon generation from atomic ensembles. We present then the last piece of evidence for the superradiant nature of such process, reporting the observation of an accelerated emission of the photon with a rate that may be tuned by controllably changing the number of atoms in the ensemble. Such investigation paves the way to a new, bottom-up approach to the study of superradiance.
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. The goal of our research is to study coherent transport of photons in cold atomic samples. One important aspect is the quest of Anderson localization of light with cold atoms and its relation to Dicke super- or subradiance. In this talk I present our latest results on Dicke sub- and superradiance.
We study the scattering of normally irradiated gyroelectric and gyromagnetic core-shell cylinders for p- and s-polarizations, respectively. Using the Lorenz-Mie theory, we derive multiple scattering quantities in the diffusion regime and weak disorder approximation of the radiative transfer equation. In particular, we calculate the energy transport velocity and the transport mean free path for two-dimensional disordered medium. Our system consists of parallel microcylinders composed of a dielectric core of $SiO_2$ and a semiconductor shell of $InSb$ with realistic material parameters, irradiated by terahertz plane waves. Setting the aspect ratio of coated cylinders, we show that variations in the axial external magnetic field or temperature lead to alternating regimes of low and high diffusion in a terahertz band, effectively tuning the wave transport across the disordered medium. This result could be of interest to design magnetically and thermally tunable metamaterials.
Attractive Optical Forces from Blackbody Radiation

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Blackbody radiation around hot objects induces ac Stark shifts of the energy levels of nearby atoms and molecules. These shifts are roughly proportional to the fourth power of the temperature and induce a force decaying with the third power of the distance from the object. We explicitly calculate the resulting attractive blackbody optical dipole force for ground state hydrogen atoms. Surprisingly, this force can surpass the repulsive radiation pressure and actually pull the atoms against the radiation energy flow towards the surface with a force stronger than gravity. We exemplify the dominance of the “blackbody force” over gravity for hydrogen in a cloud of hot dust particles. This overlooked force appears relevant in various astrophysical scenarios, in particular, since analogous results hold for a wide class of other broadband radiation sources.
Neutral polarizable atoms brought close to each other can exhibit a van der Waals (or “induced dipole-dipole”) interaction: a fluctuation of the electric field polarizes one atom, which emits a radiation that polarizes its neighbor. The field the first atom receives back from the second then yields a binding energy between the two particles. This fundamental phenomenon may have important consequences at the macroscopic scale.

In the talk, I will discuss two manifestations of van der Waals interactions in macroscopic, random ensembles of point scatterers. In the first one, I will focus on the interaction aspect by considering the Casimir-Polder force between an isolated atom and a random collection of other atoms. The Casimir force here results from radiation scattering between the probe atom and all the constituents of the macroscopic random medium. In the second scenario, I will focus on the transport aspect and discuss the effect of van der Waals interactions on the propagation of an electromagnetic wave through a dilute atomic cloud. Starting from a rigorous, energy-conserving scattering approach, I will show how these interactions affect fundamental transport properties such as the energy transport velocity or the transport mean free path.
Optical tweezers (OT) are single-beam laser traps for neutral particles, usually applied to dielectric microspheres immersed in a fluid. The stiffness is proportional to the trapping beam power, and hence can be tuned to very small values, allowing one to measure femtonewton forces, once the device is carefully calibrated. In this work, we employ OT to measure the Casimir (or retarded van der Waals) force between polystyrene beads in a fluid, for distances between 50 and 500 nanometers. The spherical beads have diameters ranging from 3 to 7 micrometers. This configuration is well beyond the validity of the commonly employed Proximity Force (or Derjaguin) approximation (PFA), thus revealing unprecedented features of the Casimir interaction. For the comparison with experimental data, we compute the Casimir force using the scattering approach applied to the spherical geometry. We also present experimental results for the total force between a mercury microdroplet and a polystyrene bead immersed in ethanol, with similar distances and diameters.
Cooperative coupling between optical emitters and light fields is one of the outstanding goals in quantum technology. It is both fundamentally interesting for the extraordinary radiation properties of the participating emitters and has many potential applications in photonics. Although this goal has been achieved using high-finesse optical cavities, attention has turned to broadband, easy to build cavity-free approaches. Here we demonstrate cooperative coupling of ultracold atoms with surface plasmons propagating on a plane gold surface. While the atoms are moving towards the surface they are excited by an external laser pulse. The interaction between the excited atom fluorescence and surface plasmons is probed by detecting the photons emitted into the substrate when the plasmon excitations decay. A maximum Purcell factor of $\eta P = 4.9$ is reached at an optimum distance of $z = 250 \, nm$ from the surface. The coupling leads to the observation of a Fano-like resonance in the spectrum.
Dicke’s superradiance is a phenomenon in the context of cooperative scattering of light where the spontaneous emission is coherently enhanced by a system of N particles. In the past many works were performed in inverted systems (where many atoms are excited by the incident light), but since 2006 a regime called “single photon superradiance” (where there is only one excited atom) has been investigated, mainly in large samples. In cold atoms, this regime is also known as the linear optics regime and it is achieved by a weak and far-detuned laser which interacts with the cold atoms. After the steady state is reached, the incident laser is switched off and the emitted fluorescence is collected to measure the superradiant decay rate. Theoretical works predict, as a main result, a fluorescent emission in the forward direction of the incident laser.

Here, we demonstrate superradiance out of the forward direction (off-axis superradiance) in a dilute cloud of cold Rb atoms, in the linear optics regime. The physical system is described by a scalar coupled-dipole model for N two-level atoms and large detuned light. In the experiment, the Rb atoms interact with a sequence of pulses obtained from an AOM and an EOM in series. The superradiant decay rates are extracted from a fit of the measured fluorescence.

We show numerically and experimentally how it is possible to have off-axis superradiance. Far from resonance, the superradiant decay rate increases with the on-resonance optical thickness. The validity of the measurements is checked from the investigation of the superradiant decay rates for different intensities of the probe beam.
We present a theoretical and experimental study of the mechanism of extraction of information stored in a quantum memory. The memory contains a single excitation of a collective atomic state, which is mapped into a single photon during the reading process. A theory is developed for the wavepacket of the extracted photon, leading to a simple analytical expression depending on the key parameters of the problem, like detuning and the intensity of the read field and the number of atoms in the atomic ensemble. This theory is compared to a large set of experimental situations and a satisfactory quantitative agreement is obtained. We were then able to make a detailed study of the single-photon superradiance in the system, since the superradiant behavior is associated to a single fitting parameter of the experimental curves. In particular, we showed that the effect of superradiance in the single-photon emission increases linearly with the number of atoms of the quantum memory, as expected from the Dicke theory.
Nonlinear effects in the cooperative scattering by cold atoms

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We studied the impact of inelastic scattering from strongly driven, saturated atomic dipole transitions, calculating the power spectrum of the scattered light diagram. Modification of the satellite rays in the well-known Mollow spectrum, both in frequency shift and line width have been investigated. Understanding this dephasing mechanism, induced by quantum mechanical frequency fluctuations of the scattered photons, is important for the transition from weak to strong localization, which is expected to occur at increased atomic densities, when atoms exchange multiple photons, and even a single photon is able to saturate the atomic transition.
In this presentation we analyze the frequency redistribution of light diffused by a resonant vapor. We have developed a Monte-Carlo simulation that allows us to follow the evolution of the emission spectrum as a function of the number of scattering events suffered by the light. For an incident light at the line center Complete Frequency Redistribution occurs after a few scattering events and the light transport exhibits anomalous diffusion behavior (Lévy Flights). For excitation at some Doppler width from the line center, correlation between incident and emitted frequency at each scattering events implies in the subsistence of emission far from resonance and a normal diffusion behavior. We also investigate the how the ratio between Doppler and homogeneous width of the vapor influences the frequency redistribution and the photon step size distribution.
Cooperative atom-light interaction in cold atomic samples has been the subject of intense investigation in the last few years. In such systems, the Doppler broadening of the spectral lines is negligible and the atom-atom interaction can dominate over the other energy scales. This two ingredients can lead to the cooperative two-photon absorption by a pair of atoms or molecules. The first experimental observation of such effect in a cold atomic system was done in a MOT of sodium atoms. In this experiment, the cooperative two-photon excitation peak was observed at halfway between the D1 and D2 transitions and showed a quadratic scaling with respect to the excitation laser intensity, which is the expected signature for the effect. The asymmetric profile of the two-photon excitation line provided an additional evidence of the interaction potential between the two atoms. Here, we propose a new experiment to investigate this effect in a Bose-Einstein condensate of sodium atoms. The increased density of these samples and the possibility to tune the atomic interaction through Feshbach resonances will allow to investigate the dependence of the excitation line shape and intensity on the interaction strength. The spatial coherence of the BEC can also be studied through the measurement of the two-photon excitation probability as a function of the displacement of two slightly detuned excitation laser beams. Finally, the ability of this system to generate correlated photons at different frequencies will be characterized by temporal correlation measurements of the atomic fluorescence signal.
Cooperative frequency shift in three-photon resonant four-wave mixing

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Modifications of resonant absorption and emission spectra lines by dense atomic samples are of fundamental importance in the investigations of a variety of quantum and nonlinear phenomena. In fact, intriguing properties can be obtained when many atoms collectively interact via a common electromagnetic field, such as Dicke superradiance and cooperative frequency Lamb shift [1]. In this work, we report on the investigation of the nonlinear response of a rubidium vapor, in which case two- and three-photon resonant transitions are driven by a four-wave mixing process. The experiment is performed with nanosecond lasers, using two beams in a non-collinear configuration, i.e., \( \theta \neq 0 \), and high atomic density. In particular, the coherence induced on the three-photon resonant transition from 5s to 6p states, excited via intermediate Rydberg states, unveiled interesting features related to the interaction of the atoms with the internally generated radiation field [2]. First, the odd-photon destructive interference between the incident and generated fields, observed in a collinear configuration (\( \theta = 0 \)) [3], is strongly inhibited for \( \theta \neq 0 \). Second, and most importantly, the three-photon transition presents a cooperative frequency shift, which decreases as the angle \( \theta \) between the two excitation beams increases and increases linearly with the atomic density. The results are consistent with the Maxwell-Bloch equation, when the generated radiation field is considered self-consistently. The measured frequency shift is strongly enhanced for small, but nonzero values of \( \theta \), due to the factor \( (1 - \cos \theta)^{-1} \), in agreement with the description based on a cooperative frequency shift.

Gravimetry with in vivo monitoring of matter waves

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Collective scattering of light can be employed for non-destructive monitoring of the dynamics of matter waves provided the light-matter interaction occurs in a ring cavity, where the scattered light can be coherently recycled in the counterpropagating cavity mode. We propose to apply this idea to monitor in vivo the Bloch oscillations of ultracold atoms in an optical lattice under the action of a constant external force. In the proposed scheme, the atoms interact with a unidirectionally pumped optical ring cavity whose one arm is collinear with the optical lattice. We find that the feedback provided by the cavity field on the atomic motion synchronizes Bloch oscillations via a mode-locking mechanism, steering the atoms to the lowest Bloch band. It also stabilizes Bloch oscillations against noise, and even suppresses dephasing due to atom-atom interactions. Furthermore, it generates periodic bursts of light emitted into the counter-propagating cavity mode, providing a non-destructive monitor of the atomic dynamics.
Within the UK Quantum Technology Hub on sensing and metrology we are currently involved in theoretical studies of gravity and magnetic sensors based on nonlinear atom interferometry. More specifically, we are devising a protocol that may be implemented in a two-component trapped Bose-Einstein condensate and surpasses the super-Heisenberg sensitivity scaling. This particular research area helps further our understanding of potential nonlinear interferometric applications and is relevant for the future development of portable and practical sensing devices.
Coherent scattering of light from ultracold atoms involves an exchange of energy and momentum introducing a wealth of non-linear dynamical phenomena. As a prominent example particles can spontaneously form stationary periodic configurations which simultaneously maximize the light scattering and minimize the atomic potential energy in the emerging optical lattice. Such self-ordering effects resulting in periodic lattices via bimodal symmetry breaking have been experimentally observed with cold gases and Bose-Einstein condensates (BECs) inside an optical resonator. Here we study a new regime of periodic pattern formation for an atomic BEC in free space, driven by far off-resonant counterpropagating and non-interfering lasers of orthogonal polarization. We predict that in suitable geometries roton instabilities originating from non-linear free space atom light interactions can be tailored to generate stationary crystalline states. They involve an optical lattice showing an emergent spacing and phononic excitations, trapping the atoms at the intensity maxima.

The required translation invariant, mirror symmetric geometry can be realized using two orthogonal polarization degrees of freedom or frequency shifted counterpropagating beams. We estimate that the dynamics studied in this work should be accessible in already existing experimental setups on large quasi-1D Bose-Einstein condensates. Actually, in comparison with standard crossed beam dipole traps, one simply has to adapt and control the polarizations of the trapping lasers and choose suitable detunings. The ordering process should be easily observable not only by measuring the atomic distributions but directly by looking at the reflected light from the condensate. This non-destructive measurement allows for a real-time monitoring of the dynamics. Our results open up an intriguing new direction in quantum simulations with ultracold atoms in optical lattices, where the latter are enriched by the presence of collective phononic excitations resulting from the spontaneous crystallisation of light. In this spirit, the application of our approach to two-dimensions and the inclusions
of retardation effects as well as quantum fluctuations constitute the natural extension of this study.

In contrast to previous works, no spatial light modes are preselected by any boundary conditions and the transition from homogeneous to periodic order amounts to a crystallization of both light and ultracold atoms breaking a continuous translational symmetry. In the crystallized state the BEC acquires a phase similar to a supersolid with an emergent intrinsic length scale whereas the light-field forms an optical lattice allowing phononic excitations via collective back scattering. The studied system constitutes a novel configuration allowing the simulation of synthetic solid state systems with ultracold atoms including long-range phonon dynamics.
We show that the decoherence rate of an open quantum system can be decomposed into a local contribution, related to the amplitude of this physical process responsible for the decoherence, and into a non-local contribution which captures the relevance of the process with respect to which-path information on the system. Both terms arise naturally in the framework of the influence functional, in the form of imaginary phase contributions. The non-local phase can be understood in terms of coupling between the backward and forward histories in the influence action. While the local phase always yields a positive decoherence rate, the non-local phase may provide a recoherence when only partial information about the system is obtained from the disturbed environment. We discuss these concepts in the framework of atom interferometry in an optical lattice.
Recent experimental developments in quantum simulators with lattice spins in ion traps have necessitated the search for numerical techniques that adequately describe their dynamics. While methods based on matrix product states have been successful with one-dimensional systems up to intermediate time-scales, computational methods of equivalent accuracy for larger dimensions remain elusive. I will present a novel method that is suitable for simulating the dynamics of quantum spin models of any dimension. The method samples the many body Wigner function and evaluates the evolution equations obtained from the Bogoliubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy. Higher orders in the hierarchy allow for systematic refinements. Quantum correlations can be treated through both, the Wigner function sampling and the BBGKY evolution, bringing about highly accurate estimates of correlations and entanglement witnesses. The method is particularly suitable for nonintegrable systems, especially those with long-range interactions. I will demonstrate its efficacy by comparing with exact results, as well as other numerical methods. Finally, I conclude with outlooks into modelling the Lindblad dynamics of the collective scattering of classical light by cold quantum gases, especially phenomena like superradiance, as well as experimental corrections in lattice spin simulators due to decoherence.
Collective atomic emission and its interplay with motional effects in dense clouds of $Sr$ atoms

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Understanding interactions between light and matter in a dense atomic medium is a long-standing problem in physical science. In addition to their fundamental importance in optical physics, such interactions play a central role in enabling a range of new quantum technologies including optical lattice atomic clocks and quantum networks. Here, we report how experimental results of collective light emission from a coherently driven ultracold gas of Strontium atoms at JILA (Boulder, USA) can be theoretically understood from a microscopic model of radiating quantum dipoles. In particular, we report on how the motion of the atoms affects the interaction induced broadening and shifting of the emitted line-shape. These motional effects can be experimentally identified in micro-Kelvin temperature Strontium gases, by making use of two atomic transition, a strong and a weak one with natural linewidths of 32 MHZ and 7.5 kHz, respectively.
We investigate the cooperative behaviour of regular monolayers of driven two-level dipoles, using classical electrodynamics simulations. The dipolar response results from the interference of many cooperative eigenmodes, each frequency-shifted from the single resonant dipole case, and with a modified lifetime, due to the interactions between dipoles. We show how subradiant behaviour of the dominant eigenmode in a two-dimensional triangular or square dipolar lattice can lead to significant enhancement in the optical extinction of a resonant driving field [1]. Such an enhancement in the optical cross section is an enticing goal in light-matter interactions, due to its fundamental role in quantum and non-linear optics. Also of interest is the kagome lattice, where the semiregular geometry permits simultaneous excitation of two dominant modes, one strongly subradiant, leading to an electromagnetically-induced-transparency-like interference in a two-level system. The interfering modes are associated with ferroelectric and antiferroelectric ordering in alternate lattice rows with long range interactions [2].

Intrinsic Optical Bistability in a Rydberg ensemble

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The optical bistability is a phenomenon which has been receiving considerable attention by providing a rich contribution to the understanding of the non-equilibrium systems. Intrinsic Optical bistability originates when the bistability arises in a system without external cavity, where the dynamical equilibrium, necessary for these observations, is provided by a driving field excitation and the dissipation due the atom-atom interaction [1]. In this work, we investigate intrinsic optical bistability in a diluted ensemble of cesium atoms. For this, we use a three photon excitation scheme, where three lasers co-propagating are focused in a 2mm vapor cell and, using an interference filter, we measure the transmission of a probe beam. We observe phase transition between two phases, low and high, of Rydberg occupancy and an intrinsic optical bistability for a big range of Rydberg states [2]. The behavior of the hysteresis window width is investigated for different parameters like atomic density, principal quantum number and the power of the excitation laser. The experimental results reveal widening of the hysteresis window and a subsequent narrowing with the increase of the principal quantum number. Also, we observe a saturation of the hysteresis window whilst the power of the excitation laser is increased. The experimental results show good agreement with the prediction from a simple theoretical model based on semiclassical Maxwell-Bloch equations including the effects of self-broadening and frequency shift. Furthermore, we are able to find the numeric value for the self-broadening coefficient involving Rydberg levels [3]. This work was supported by Durham University, EPSRC (Grant No.EP/M014398/1 and EP/M013103/1), CNPq and FACEPE (Brazilian Agencies).