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Progress in Physics (90)

Quantum simulation with atoms and photons

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Quantum simulation, i.e. the use of a fully controlled quantum device to understand the properties of complex many-body systems, is among the most important applications of emergent quantum technologies. Among the platforms available for this task, ultra-cold atoms are the most widespread, thanks to their native ability to represent both Bosons and Fermions, to explore a wide range of geometries using laser-induced potentials, and the possibility to reach the strongly interacting regime. Here, we present the use of cavity quantum electrodynamics together with cold atomic gases to realize novel types of quantum simulations. We review the different ways by which cold atoms can couple with light, and describe their applications to quantum simulations of models involving long range interactions.

Cavity quantum electrodynamics (cQED) allows for the control of light-matter interaction at the single mode and single photon level [1]. In general, a set of mirrors or waveguides controls the electromagnetic environment, singling out one or a small set of electromagnetic field modes. In the optical domain, this is achieved in the simplest instance using two mirrors forming a Fabry-Perot cavity, giving rise to a discrete set of Gaussian, standing wave modes. The imperfect reflection of light onto the mirrors allows to drive the cavity modes using an external field, and most importantly to detect the small photon flux leaking from the cavity using standard high-efficiency detectors.

The interaction between an emitter and light is deeply modified inside the cavity. Light scattered by the emitter is sent back coherently by the mirrors, constructively interfering to enhance emission in the mode supported by the cavity, as opposed to every other. As a result, coherent photon exchanges between the cavity mode and the emitter are enhanced compared with other irreversible processes [2]. This *cooperative* enhancement implies for instance that by reading-out the cavity field, a measurement limited by quantum mechanical back-action can be realised even for an individual emitter.

The tailored light-matter interaction allowed in cQED is a core of the emerging quantum technologies. In the micro-wave domain, it is the building block of superconducting quantum circuits. In the optical domain, it is one of the best candidates to form the nodes of quantum networks [3]. In this review, we describe the fast growing application of cQED as a tool for quantum simulation of complex quantum many-body systems with cold atoms. The capability to produce quantum many-body systems has improved in a spectacular way in the field of cold atoms in the last two decades. The combination of these methods with high-finesse optical cavities has emerged in 2007 [4, 5], with the trapping of Bose-Einstein condensates within the mode of a cavity. Since then, combined systems of atoms and cavities have grown to reach higher and higher degrees of sophistication, integrating many of the technological innovations available in both atomic physics and quantum optics [6]. We first describe how light in the cavity can couple to a many-body system, and help uncovering the correlations between particles, and then present the use of the cavity to synthesize an interaction between particles, allowing for the experimental realization of a new class of many-body models featuring long-range interactions. We conclude by giving some perspectives for the future of this fast-growing field.

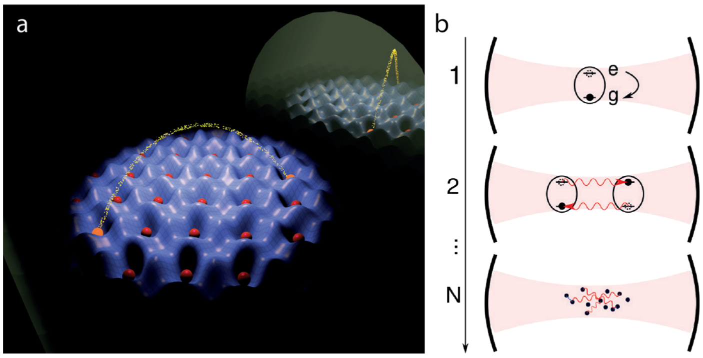

FIG. 1. (a) Artistic illustration of cavity mediated long-range interactions: Two atoms (pale red) interact with each other via the exchange of photons (yellow) stored in a cavity mode, defined by two mirrors facing each other. (b) Conceptual scheme: 1) a single atom exchanges an interaction with a cavity mode. 2) Two atoms mutually exchange an interaction via virtual photons mediated by a cavity mode. N) A (quantum) many-body system of N atoms coupled to a cavity mode offers the possibility to engineer and detect many-body phases with long-range interactions.

I. Interaction of Light with Many Atoms

The interaction of a single emitter with one mode of the electromagnetic field is described by the Jaynes-Cummings model, a textbook example of quantum optics systems describing coherent exchange of photons between the cavity and a two-level atom, as illustrated in figure 1b. For systems of high cooperativities, the coherent atom-light coupling dominates over decoherence processes, for instance the scattering of a photon out of the cavity by the atom or through the mirrors [2].

With two atoms present in the cavity, they couple simultaneously and coherently to the same cavity field. As a result, a coherent bright state where a single excitation is shared between the two atoms emerges, yielding a $\sqrt{2}$ enhancement of light-matter coupling. For a cavity detuned with respect to the atomic resonance, the emission of light by one atom in the cavity is suppressed, but the photon exchange between atoms persists as a resonant second order process, similar to super-exchange in the condensed matter context. This is a spin-exchange interaction, mediated by virtual photons in the cavity [7]. This interaction derives from the coupling of atoms with the cavity photons, so it inherits the spatial structure of the cavity mode, making the interaction range infinite. This contrasts with typical interactions between neutral atoms, and has some similarities with phonons in trapped ion chains [8]. The spin-exchange mechanism is most easily understood for simple two-level systems, but it can be generalized to multilevel atoms, in particular to Raman processes involving different hyperfine ground states [9].

For N atoms, a single bright state forms, comprising a single excitation shared between all the atoms with $\sqrt{N}$ enhanced coupling to light. This coherent effect, while resulting from the presence of many particles, does not as such carry any particular connection with the possible correlations existing between these in the absence of interaction with light. This enhanced light-matter coupling is very general and has been observed in a wide range of systems, from thermal and quantum degenerate atomic Bose [4, 5] and Fermi gases [10], to semiconductor [11] or two-dimensional materials [12].

In the detuned regime where the cavity is only virtually populated, the system is described by a non-linear collective spin model. This mechanism has been first leveraged to create spin squeezing for metrology applications [14, 15]. Recently, this has been used for the quantum simulation of quantum magnetism in the Lipkin-Meshkov-Glick model [13]. The collective spin description is a natural consequence of the single-mode nature of the cavity. It is nevertheless possible to go beyond by dividing the atomic ensemble into subsets with tunable resonance frequencies, yielding the emergence of a synthetic geometry [16]. One strength of quantum simulations applied to spin models is that the cavity-mediated interaction addresses internal degrees of freedom of atoms, making it possible to use thermal, non-interacting gases as basis system and to disregard motional degrees of freedom.

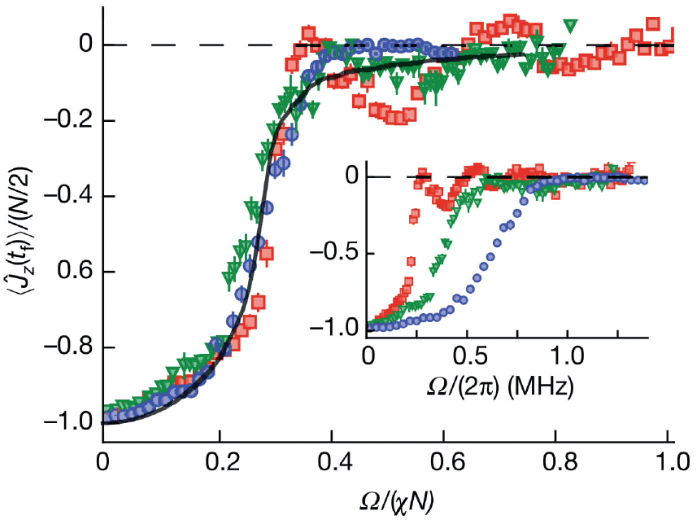

FIG. 2. Quantum simulation of quantum magnetism with an atomic ensemble coupled to a cavity, described by the Lipkin-Meshkov-Glick model. Two internal states of atoms represent the two states of quantum spins. The curve shows the average magnetization per spin $\langle \hat{J}_z\rangle/(N/2)$ as a function of transverse field Ω in units of the spin-exchange interaction strength $N\chi$. This shows a ferromagnetic-paramagnetic dynamical phase transition. Inset: same data prior to finite-time scaling. Adapted from [13].

II. Interaction of Light with a Many-Body System

Our description of light-matter interaction so far does not depend on the possibility that the atomic medium may have on its own intrinsic correlations. Quantum degenerate atomic Bose and Fermi gases have proven to be a powerful platform for the simulation of a broad range of intriguing quantum many-body phenomena [17]. The excellent control over internal and external degrees of freedom, as well as the tunability of the short-range inter-atomic collisional interaction, allows to bring fundamental interactions in the low-energy sector into competition. There, the quantum statistic of atoms, as well as the potential landscape play a key role in the emergence of quantum phases, most prominently superfluidity. At first sight, cQED enhances the light-matter coupling to energy scales far exceeding that of the motional degrees of freedom in quantum degenerate gases, making the exact state of the gas irrelevant. However, higher-order processes involving either two photons or two atoms can bring light-matter interaction and many-body physics in the gas to similar scale, which opens an entire new research field: many-body cavity QED [6].

A. Real-time measurements

While the detection process in quantum gas experiments is almost always destructive, the settings of cQED allows for minimally invasive, real-time readout of the properties of the many-body system. The coherent scattering of light by the atomic system into the cavity mode provides a novel tool to investigate quantum phases, as has been proposed for the non-destructive detection of Mott-insulating and superfluid phases [18].

Another mechanism consists in the coupling of one photon to pairs of atoms through photo-association into excited molecular states. Photo-association is a well known physical chemistry process, of high importance for the realization of molecular quantum gases [19]. In the cQED settings, it allows for one photon to be coherently coupled to a pair of atoms. The corresponding Rabi frequency encompasses both a purely electronic contribution, the intrinsic electric dipole coupling of the molecular state to light, and a Franck-Condon overlap factor between the two-body wavefunction in the ground state and the target molecular state. The latter implies that in contrast with light-matter coupling at the single atom level, the strength of photo-association transitions measures the degree of pair-correlations in the gas [20, 21]. The use of cQED to address these transitions allows then to map the pair-correlations of the gas onto the cavity spectrum, where the Rabi frequency can be directly read-out. This has been used for a unitary Fermi gas, a paradigmatic example of strongly correlated Fermi systems realized with cold atoms [22]. In addition, it even allows for the weak contribution of photo-association to the index of refraction of the gas to be precisely measured, generalizing cavity-assisted, weakly destructive measurements [23] to pair-correlations in quantum matter.

B. Backaction and light-mediated interactions

In the examples mentioned in the previous section, the coupling between the atomic system and the cavity field was sufficiently weak such that the measurement had negligible backaction onto the state of the many-body system. Howev-

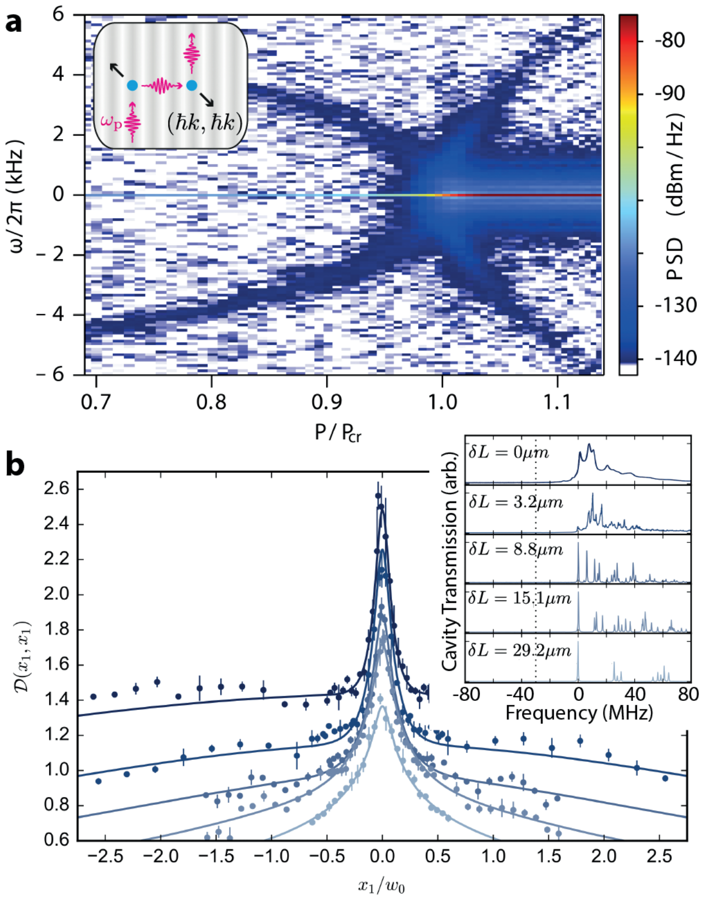

FIG. 3. a) The dynamic structure factor of a quantum gas undergoing the self-organizing quantum phase transition is directly proportional to the power spectral density PSD of the light field leaking out of the cavity. The PSD is shown as a function of frequency shift ω with respect to the pump field frequency and relative transverse pump power P. Two sidebands are visible, corresponding to the incoherent creation ($\omega < 0$) and annihilation ($\omega > 0$) of quasi-particles. The energy of these quasi-particles softens towards the critical point. At the phase transition ($P/P_{cr} = 1$), a strong coherent field at the pump frequency ($\omega = 0$) signals the buildup of a crystalline structure. The inset displays the microscopic processes where photons mediate an interaction between pairs of atoms. Adapted from [24].
b) Tunable-range cavity-mediated interatomic potential in a multi-mode cavity. Shown is the absolute value of the strength of the effective self-interaction potential for a small BEC. The different colors correspond to different degrees of degeneracy of the cavity modes which can be tuned via the cavity length as shown in the inset. The pump frequency is indicated by the dotted line. Adapted from [25].

er, these systems can also be tuned to regimes where this backaction is strongly influencing the physics.

A prominent example is the cavity optomechanical coupling [26] between the collective motion of the atoms and the light field in a cavity driven with a laser [27–30]. In the dispersive regime, where the frequency of the light field is far detuned from atomic resonance, the atomic cloud acts as a medium with an effective refractive index. The cavity resonance frequency, which also controls how much light from the driving laser enters the cavity mode, is thus shifted depending on the spatial overlap between the atomic system and the standing wave cavity mode. At the same time, the intra-cavity light field acts as optical dipole potential for the atoms, which arrange in a lattice structure according to the depth of this potential. This mutual coupling gives rise to a selfconsistent evolution, where the intra-cavity field depends on the atomic motion and the atomic motion depends on the field. This creates a feedback mechanism between the atomic motion and the light field. The coupled system is a direct realization of a mechanical oscillator coupled to light in cavity-optomechanics, with an extreme recoil-to-coupling ratio [31].

The coupled evolution of light and matter can lead to spectacular self-organization processes, when the atomic cloud is directly illuminated by a standing wave laser field transversely to the cavity mode [32–35]. The scattering of photons from this pump field into the cavity is strongly enhanced by the cooperativity. However, for a spatially homogeneous gas, the light scattered by all atoms destructively interferes and the cavity remains unpopulated on average. Coherent scattering into the cavity is only possible if the atomic cloud is spatially modulated in a chequerboard pattern forming Bragg planes that support constructive interference. For a quantum gas, such imprinting of a modulation is suppressed by the kinetic energy cost required to accordingly bend the atomic wave function. In a microscopic picture, the scattering process imparts the photon recoil momentum onto the atom. The photon recoil energy, i.e. the kinetic energy associated with the density modulation, thus competes with the light-scattering process. Only for a sufficiently strong pump field does the emergent potential formed by the interference of the pump and cavity field overcome the kinetic energy cost, leading to a phase transition into a self-organised chequerboard pattern. The interplay of motional degrees of freedom with the cavity field manifests in the case of Fermions by Pauli blocking and Fermi surface nesting effects [35].

Similar to cavity-assisted spin-exchange, this mechanism can also be understood as a cavity-mediated atomic interaction: two atoms interact by scattering a photon from the pump field into the cavity at the first atom, and then back into the pump field at the second atom. Since the scattered photon is delocalized over the entire cavity mode, this effective interaction is periodic in space and of global range. The self-organized phase described above is then interpreted as a spontaneous density wave ordering, with a structure inherited from the interference between pump mode and cavity mode. This homogeneous to density wave transition occurs whenever the interaction energy balances the kinetic energy. At the transition, the system breaks the discrete Z(2) symmetry of the emerging chequerboard pattern, where the atomic density is enhanced on either the even or the odd sites. The fluctuations driving this transition are the density fluctuations of the superfluid, see Fig. 3a. From the quantum-optics point of view, this phase transition can also be interpreted as realization of the Dicke-Hepp-Lieb phase transition [36, 37] between a normal and a superradiant state of matter. This mapping made it possible to experimentally explore this paradigmatic phase transition and its properties in detail [6].

Making use of the cavity-mediated interaction in systems going beyond the coupling to a single cavity mode allows to realize a number of intriguing physical concepts. By coupling a Bose-Einstein condensate to two crossing optical cavities which are degenerate in frequency, scattering of photons into the spatially well separated modes comes at the same energetic cost, but results in very different emergent atomic crystals. Instead of breaking a discrete Z(2) symmetry, in this case a continuous U(1) translational symmetry is broken. The origin of the emergent crystalline structure is then free to move in space depending on the relative population of the two cavity modes. This realizes a supersolid state of matter [38], where at the same time a continuous spatial symmetry and a continuous gauge symmetry are broken, since the system is a superfluid.

The cavity-mediated global-range interaction can further be engineered to become an interaction with tunable range by coupling to thousands of energetically degenerate but spatially distinct cavity modes. Such a situation is realized in confocal multi-mode cavities, where the mirrors are placed such that a large number of higher transverse electromagnetic field modes become degenerate, see Fig. 3b. While the emergent crystal for global range interactions is infinitely stiff, these finite-range photon- mediated interactions lead to crystalline structures that support sound modes [39]. This additional control over cavity-mediated interaction allows to investigate elasticity in quantum solids, but also has the prospect to realize systems known from soft condensed matter [40].

Cavity-mediated interactions can also be made to compete with the intrinsic atomic collisional interactions, which gives rise to the formation of strongly correlated quantum phases. Kinetic energy, collisional interactions, and cavity-mediated global-range interactions can be brought to the same energy scale by loading the atoms into an external three-dimensional optical lattice and coupling them at the same time to a cavity. Such a configuration realizes an extended Bose-Hubbard model whose phase diagram features superfluid, lattice supersolid, Mott insulating and charge density wave phases, which can be explored in real time via the light field leaking from the cavity mode [41].

III. Perspectives

Quantum simulation is one of the most active applications of currently available intermediate-scale quantum technologies. In this framework, quantum gases in optical cavities offer a promising avenue for the study of many-body physics. Compared with cold atoms in optical lattices or arrays of Rydberg atoms, the cavity features a native and engineerable all-to-all coupling. This is similar in spirit to trapped ion-chains, but with a natural scalability to large ensembles, at the cost of limited access to individual atoms. Compared with qubit-based intermediate-scale quantum computers, the cavity-based quantum simulation platform intrinsically features many-body physics ranging from strongly interacting insulating phases to Fermi statistics which are notoriously costly to simulate digitally.

The cavity photons share a lot of features with phonons in the condensed matter context. The self-organization transition is then analogous to charge density wave ordering, opening interesting perspectives for the study of the interplay of charge order with superfluidity or magnetism, which is ubiquitous in strongly correlated materials. Extensions of cavity-based quantum simulations can also make use of the rich internal structure of the atoms, in order to study spin texture formation [42] and dynamic spin-orbit coupling [43].

The settings of cavity QED features a controlled dissipation channel in the form of photons leaking through the cavity mirrors, allowing for the study of models beyond unitary evolution. Non-thermal steady states and complex emergent dynamics have already been observed [44, 45], and the setting is perfectly suited to explore properties of dissipative phase transitions.
The interplay of cavity QED with many-body physics further opens fascinating perspectives for applications to metrology, by which the correlations between atoms induced by the cavity can be used to reduce noise below the standard quantum limit in atomic clocks. Beyond clock operations, superradiant emission from correlated atoms is one of the most promising tool for pushing optical atomic clocks beyond the state of art precision.

The recent technological developments, in particular with commercially available stable and reliable laser systems, allows now to combine cavity QED systems with well established quantum simulation tools, such as optical lattices or tweezer arrays. In this framework, the unique features of many-body cQED, such as continuous readout and the all-to-all coupling geometry constitutes a major asset for future quantum simulations of condensed matter physics models and beyond.

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Tobias Donner is senior scientist at ETH Zürich. He completed his PhD in 2008 under the guidance of Tilman Esslinger at ETH Zürich. During a postdoctoral stay at JILA in Boulder (USA) he achieved the first ground state cooling of a cavity optomechanical device. Since 2013 he leads a cavity quantum electrodynamics laboratory together with Tilman Esslinger, where he is a pioneer in many-body cavity QED and, for example explored the Bose-Hubbard model with long-range interactions and demonstrated the first realization of a supersolid state of matter.