BOOK OF ABSTRACTS (PRELIMINARY)

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Cavity cooling of a large number of strongly-confined particles

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Currently, the most effective technique for the cooling of a large number of particles to very low temperatures is evaporative cooling [1]. It requires the systematic removal of those particles with a relatively high temperature from the trap and is commonly used for the preparation of Bose Einstein condensates. The particles can reach very low temperatures but only a very small percentage of them is finally included in the condensate. If one could instead cool particles efficiently, yet at the same time avoid the loss of most of them, it should become much easier to experiment with large condensates. Such a cooling technique would open new perspectives for experiments which study the fundamental properties of quantum mechanical particles, including cold atoms, ions and molecules, but would also facilitate applications like the simulation of condensed matter systems.

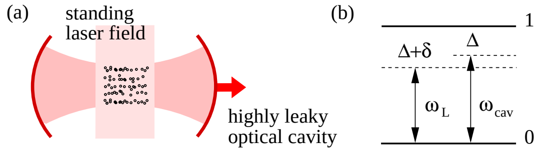

FIG. 1: (a) Schematic view of the experimental setup consisting of N two-level particles trapped inside a highly leaky optical cavity in the presence of a red-detuned standing wave laser field. (b) Level configuration of a single particle.

Here we consider a large number of particles trapped inside an optical cavity. As in Ref. [2] we assume that their confinement is so strong that the particle motion becomes quantised. An externally applied laser field hence establishes a coupling between the electronic states of the particles with the phonons *and* the photons in the setup. The result is the conversion of phonons into cavity photons and vice versa. For most system parameters, this results in the heating of the particles and their eventual ejection from the trap. However, our calculations also identify a parameter regime in which the particles possess a relatively stable stationary state with a very low phonon number. We show that a relatively leaky and highly detuned optical cavity, like the one in the 1997 cavity experiment of Grangier's group in Paris [3], can be used to cool particles to very low temperatures without having to remove most of them from the setup.

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C++QEDv2 and applications: a domain-specific language and framework for simulating open interacting quantum dynamics

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A domain-specific language (DSL) is a high-level programming language, where the very syntax provides for both ease of use, and enforcement of correct usage in a specific application domain. In the present paper we report on C++QEDv2, a DSL embedded into C++, which has been developed for the last two and a half years. C++QEDv2 comprises three aspects:

1. It is a C++ library for efficiently simulating open interacting quantum dynamics of arbitrarily complex systems in general, and moving-particle CQED systems in particular. In this aspect, it can become a replacement of the popular Quantum Optics Toolbox of Matlab, especially in situations where the use of the latter is prohibitively expensive in terms of computational resources.

2. It is a *specification* of a DSL for describing open interacting quantum systems in general, and quantum optical systems in particular. The above-mentioned library can be thought of as an *implementation* of this specification.

3. As an engine of the DSL, the framework applies a number of new design patterns which should be generic for very high-level simulations of composite quantum systems. They rely on a very particular newer aspect of C++: massive algorithms executed at *compile time*. By shifting calculations from runtime to compile time, we can significantly cut on the former in many situations.

After touching on the three aspects above, we shall also present recent applications of the framework in the field of moving-particle CQED in our group.

The topic of the paper is hence a compromise between ”C++ design for quantum opticians”, ”computational physics for quantum opticians”, and actual ”quantum optics”.

Cavity-enhanced Rayleigh scattering

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In recent years, the field of cold and ultracold polar molecules has received a lot of attention. Sensitive, non-destructive detection techniques for molecules would be of great help for different applications. Optical cavities facilitate such detection, as has been demonstrated with atomic systems. However, the transition from atoms to molecules is not straightforward, due to the complex internal structure of molecules.

Here, we make a first step towards cavity-based detection of cold molecules. We report on measurements of cavity-enhanced Rayleigh scattering into an optical Fabry-Perot resonator using several room-temperature atomic and molecular gases. The laser light is far detuned from any optical transition. The observed enhancement factors of up to 38 are in good agreement with theoretical predictions based on the classical model of a driven oscillator and light waves interfering inside the cavity.

Cavity-QED with cold ion Coulomb crystals

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Cavity Quantum Electrodynamics (CQED) is a powerful platform for the realization of efficient light-matter quantum interfaces at the single photon level. Laser-cooled, trapped ions offer many attractive features for CQED, namely long coherence and trapping times, low densities and excellent localization. Using a novel linear ion trap incorporating a high-finesse optical cavity along its axis [1] we have realized such an interface with a cloud of cold ions, cooled to a self-organized Coulomb crystal structure. This allowed us to observe for the first time collective strong coupling between cold ions and a cavity field at the single photon level [2]. We will present results on the characterization of the ion-cavity field coupling and on the coherence times of collective sub-Zeeman coherences, measured to be in the millisecond range, as well as discuss the promising applications of ion-based CQED using ion Coulomb crystals.

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Cooling and entanglement in optomechanical systems

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We provide a general framework to describe cooling of a micromechanical oscillator to its quantum ground state by means of radiation-pressure coupling with a driven optical cavity. We apply it to two experimentally realized schemes, back-action cooling via a detuned cavity [1–5] and cold-damping quantum-feedback cooling [6–9], and we determine the ultimate quantum limits of both schemes for the full parameter range of a stable cavity [10, 11]. While both allow to reach the oscillator's quantum ground state, we find that back-action cooling is more efficient in the good cavity limit, i.e. when the cavity bandwidth is smaller than the mechanical frequency, while cold damping is more suitable for the bad cavity limit. The results of previous treatments are recovered as limiting cases of specific parameter regimes. We also analyze the possibility to generate robust entanglement at the steady of the system and discuss the connection with ground state cooling [12]. We show that robust stationary entanglement between the mechanical resonator and the output fields of the cavity can be generated, and that this entanglement can be transferred to atomic ensembles placed within the cavity [13]. These results show that optomechanical devices are interesting candidates for the realization of quantum memories and interfaces for continuous variable quantum communication networks.

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Cold guided beams of polar molecules

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In this presentation, our recent studies on the velocity filtering and guiding of cold polar molecules will be discussed. With this technique high-density beams of slow polar molecules are extracted from a reservoir by means of an electric quadrupole guide. The detection signal exhibits a characteristic dependence on the strength of the applied guiding fields for different classes of molecules, as is demonstrated for the water isotopologs, H2O, D2O, and HDO [1]. The observed signals are in excellent agreement with our predictions taking into account the different Stark shifts due to the orientations of the electric dipole moments with respect to the principal axis in these similar molecules. During the beam formation, collisions between molecules affect the observed signals, especially at high reservoir pressures. The resulting modest boost in velocity is accurately reproduced by a model, which includes velocity-dependent collisional losses [2]. The number of contributing states in our beams strongly depends on the Stark shifts of the internal molecular states. In general, the extracted beam can be purified by reducing the temperature of the reservoir. However, a strong reduction of populated states is only expected at cryogenic temperatures. This is achieved by cooling the molecules by collisions with a helium buffer gas in a cryogenic cell, before they enter the electric guide [3]. By laser-induced depletion of individual states of formaldehyde inside the electric guide [4], we have observed an order-of-unity population of the lowest guidable state, showing the cooling effect of the buffer gas in a direct manner [5].

In the future, our continuous beams of cold molecules can be employed to perform high-precision experiments, to study state-specific cold collisions, and to load traps in which novel cooling techniques, such as cavity cooling [6], might bring them to the ultracold regime.

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Cavity Optomechanics with a Bose-Einstein condensate

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Cavity optomechanics studies the coupling between a mechanical oscillator and the light field in a cavity via radiation pressure. Various experimental realizations ranging from macroscale gravitational wave detectors down to microscale cantilevers have been reported on (for a recent review see e.g. [1]). An ultimate goal of these efforts is to cool the mechanical degree of freedom via the dissipative cavity decay channel to its ground state, and to study the border between classical and quantum physics.

By dispersively coupling a Bose-Einstein condensate to the field of a high-finesse optical cavity [2] we implemented a novel cavity optomechanical system with unique properties. The mechanical oscillator which is provided by a collective density excitation of the condensate is naturally prepared in its ground state. Due to our very small cavity mode volume the cavity light field couples strongly to the mechanical motion already on the level of single quanta. Accordingly, we observed bistable behaviour and coherent mechanical oscillations caused by single intracavity photons [3, 4]. Future research will concentrate on exploring signatures of the quantum regime of cavity optomechanics, as for example detecting single excitations of the mechanical oscillator mode.

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A quantum gas of molecules in the rovibronic ground state

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Ultracold samples of molecules are ideally suited for fundamental studies in physics and chemistry. For many of the proposed experiments full molecular state control and high phase space densities are needed. We create a dense quantum gas of Cs_2 molecules in the rovibronic ground state, i.e. the $|v=0, J=0>$ level of the $X^1\Sigma_g^+$ state. We first efficiently produce weakly bound molecules on a Feshbach resonance out of a Bose-Einstein condensate (BEC) of Cs atoms. These molecules are then coherently transferred without heating to the deeply bound $|v = 73, J = 2>$ level of the $X^1\Sigma_g^+$ state, bound by more than 1000 cm^{-1}, by using the two-photon STIRAP technique [1]. From this intermediate level the molecules are transferred in a second STIRAP step to the rovibronic ground state $|v=0, J=0>$ and alternatively to $|v = 0, J = 2>$. The transfer efficiency is around 80% for each STIRAP transfer step. One attractive route for the production of a BEC of ground state molecules is to produce the weakly bound molecules in a three-dimensional optical lattice and perform the STIRAP transfer while the molecules are trapped in the lattice. Subsequent release from the lattice should ideally result in the creation of a molecular BEC. We have implemented transfer to the intermediate level $|v=73, J=2>$ in the lattice with efficiencies equal to the case without the lattice [2]. We discuss the progress for the implementation of the next step, i.e. transfer of the molecules into the rovibronic ground state in the lattice. Our results show that the creation of a BEC of molecules in their rovibronic ground state is within reach.

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Electric Cooling of Polar Molecules

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An experimentally realizable scheme to cool molecules into the sub mK regime is presented. Aspects of the scheme which are considered include cooling rates, trap design and selection of suitable molecular transitions. Basic rate equations show cooling from 1K to below 100mK in 1s and cooling to below 1mK in under 10s. During this time, the molecules are enclosed in an electric trap which can be loaded with molecules from an effusive source/quadrupole guide combination as developed in our group [1]. Depending on the implementation, cooling of both internal and external molecular degrees of freedom is possible as well as an accumulation scheme, increasing the density while keeping temperature constant.

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Coherent coupling of ion Coulomb crystals to various transverse modes of a cavity field

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Collective strong coupling with ion Coulomb crystals has recently been realized for the first time [1]. This system has now been used to explore other CQED phenomena. We will present recent results of coherent coupling to various transverse modes of a cavity field which take advantage of some of the attractive features of ion Coulomb crystals. First, the high degree of spatial localization of the ions makes it possible to use a string-like Coulomb crystal for precise reconstruction of the spatial profile of the cavity mode by measuring the ion-light coherent coupling. Second, the stationarity and uniform density of large crystals ensures that identical coupling strengths are achieved with higher order modes. These results are promising for cavity mediated cooling, and combined with the long coherence times of ion Coulomb crystals [1], for multi-mode quantum state generation and storage.

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Optomechanical coupling in a one-dimensional optical lattice

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In recent papers [1, 2] we have shown that traveling density wavelike collective oscillations can arise in an asymmetrically pumped optical lattice, and by increasing the lattice size or pump asymmetry, these waves can destabilize the structure even in the overdamped limit. The long-range interaction giving rise to collective motion stems from the back-action of the atoms on the field creating the lattice. In this talk I will describe these phenomena. I will derive the force on a disk-shaped cloud of trapped particles including the back-action on the trapping light, and analyze its relation to the standard perturbative approach giving the "dipole force" and "radiation pressure." I will calculate the self-consistent lattice constant for both red and blue detuned lattices and find that it decreases – by the same amount in the two cases – as the pump asymmetry is increased. I will present the detailed derivation of the lattice vibration eigenmodes using the transfer matrix method, which reveals that the instability is enhanced resonantly at certain settings of the asymmetry. Finally, I will discuss some aspects of the "ultrastrong coupling" regime of cavity QED, in particular, the consequences of the lack of a dipole potential to derive forces in an opto-mechanically coupled system [3].

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Cavity cooling of trapped atoms and ions

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We study the cooling dynamics of atoms confined by an external potential in a high-Q cavity, when the width of the atomic wave packet is much smaller than the field wave-length. In this regime we derive an analytical expression for the quantum center-of-mass dynamics which allows us to identify novel regimes where the motion can be efficiently cooled to the potential ground state. In particular, parameter regimes are identified where the dynamics is characterized by quantum interference between the mechanical effects of the laser and of the resonator, which selectively enhance the cooling processes and thus the efficiency. In this regime we characterize the state of the system by the spectrum of the intensity of the light scattered by the atom and at the cavity output, when atom and cavity are at steady state of the cooling dynamics. We find that quantum interference effects manifest themselves in the suppression of features of the resonance fluorescence spectrum, which are otherwise visible in the spectrum of atoms in free space.

Optical lattice with a staggered magnetic field

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Using a bichromatic light-shift potential a two-dimensional square optical lattice with a time-modulation term can be realized that introduces rotation with alternating directions in each plaquette [1]. This scenario can be described by a Bose-Hubbard model with an additional staggered magnetic field [2]. Besides the uniform superfluid and Mott insulating phases, known from the conventional Bose-Hubbard model, the zero-temperature phase diagram exhibits a novel kind of finite-momentum superfluid phase, characterized by a quantized staggered rotational flux in each plaquette. An extension for fermionic atoms, which leads to an anisotropic Dirac spectrum, may be relevant for the physics of graphene and high-Tc superconductors.

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Quantum Phase Transitions and Frustration of Ultracold Gases in Multimode Cavities

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An ultracold bosonic gas, trapped in an optical cavity and transversely pumped with a laser, crystallizes at the even or odd antinodes of the cavity mode for sufficient pump intensity. In a single-mode cavity, this transition is adequately described by mean-field theory [1, 2] as all the atoms must couple to a single degree of freedom, the cavity mode. In multimode cavities, however, atoms can exchange photons through any of the cavity modes; this dramatically increases both the importance of fluctuations and the possibilities for ordering. For a quasi-2D atomic cloud, we find that critical fluctuations drive the ordering transition first-order and raise the threshold by a mechanism first explained in Brazovskii's work on lamellar systems [3]. For a 3D distribution of atoms, we consider regimes in which the system is unable to order globally, and therefore forms domains. We discuss the connection between self-organized cavity QED systems—in which Bose-Einstein condensation coexists with spontaneously broken translational symmetry—and supersolidity.

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Free-space laser cooling of polar molecules?

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For many reasons – including quantum simulation of condensed-matter Hamiltonians[1], quantum computing[2], and precision tests of fundamental physics[3] – there is a strong desire to produce samples of ultracold polar molecules at temperatures and densities similar to those found in laser-cooled atom traps. However, laser cooling of molecules has so far proven impractical, due to the large number of metastable rovibrationally excited states available for the molecules to decay into[4]. In this talk, I present a new proposal[5] for how to take advantage of the detailed properties of a specific class molecules (e.g. titanium monoxide, TiO) to enable their free-space laser cooling and trapping into a molecular magneto-optical trap.

Other people participating in this work were B. Sawyer, D. Wang, and J. Ye. We acknowledge funding support from DOE, NIST, and NSF.

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Cold guided beams of polar molecules

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In this presentation, our recent studies on the velocity filtering and guiding of cold polar molecules will be discussed. With this technique high-density beams of slow polar molecules are extracted from a reservoir by means of an electric quadrupole guide. The detection signal exhibits a characteristic dependence on the strength of the applied guiding fields for different classes of molecules, as is demonstrated for the water isotopologs, H2O, D2O, and HDO [1]. The observed signals are in excellent agreement with our predictions taking into account the different Stark shifts due to the orientations of the electric dipole moments with respect to the principal axis in these similar molecules. During the beam formation, collisions between molecules affect the observed signals, especially at high reservoir pressures. The resulting modest boost in velocity is accurately reproduced by a model, which includes velocity-dependent collisional losses [2]. The number of contributing states in our beams strongly depends on the Stark shifts of the internal molecular states. In general, the extracted beam can be purified by reducing the temperature of the reservoir. However, a strong reduction of populated states is only expected at cryogenic temperatures. This is achieved by cooling the molecules by collisions with a helium buffer gas in a cryogenic cell, before they enter the electric guide [3]. By laser-induced depletion of individual states of formaldehyde inside the electric guide [4], we have observed an order-of-unity population of the lowest guidable state, showing the cooling effect of the buffer gas in a direct manner [5].

In the future, our continuous beams of cold molecules can be employed to perform high-precision experiments, to study state-specific cold collisions, and to load traps in which novel cooling techniques, such as cavity cooling [6], might bring them to the ultracold regime.

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Ytterbium atoms in high-finesse optical cavities

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We will present the status of the experimental setup we are developing at ICFO. Ytterbium atoms will be trapped inside a high finesse cavity. The interaction of Yb atoms and the photons that are confined in such a cavity will be studied. This apparatus will be suitable for investigating the collective excitation of a cold atomic cloud interacting with the standing wave of a resonator, with the perspective of using this system for investigating new cooling mechanisms based on atom-cavity interaction. Furthermore, cavity-QED-based atom-photon interfaces which allow the deterministic interconversion between photonic and atomic quantum states are within the scope of the experiment. We observed cooling and confinement of ^{174}Yb atoms in a Magneto-Optical Trap operating on the $^1S_0 -^1 P_1$ transition ($\lambda = 399\, nm, \Gamma = 2\pi \cdot 28\, MHz$) as well as on the $^1S_0 -^3 P_1$ inter-combination transition ($\lambda = 556\, nm, \Gamma = 2\pi \cdot 182\, kHz$). At the moment we are preparing the cavity to be mounted.

Light Scattering by Ultracold Atoms in Optical Lattices

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In the first part light scattering by an ultracold atomic gas in a one-dimensional optical lattice is theoretically studied, when the atoms are probed by a weak laser. We analyze the intensity of the scattered light as a function of the angle of emission for different values of the tunneling rate, spanning from the superfluid to the Mott-insulator phase. We show how the excitation spectrum of the many body system can be measured by observing of the scattered light intensity as a function of the scattering angle and photon frequency. We identify different features in the first order coherence of the scattered light, depending on whether the atoms are in the Mott-insulator or superfluid state. We discuss our results with respect to previous studies, where the structure form factor was evaluated by a time-of-flight measurement [1] and where light scattering by ultracold atoms in an optical lattice was determined, neglecting the tunneling rate [2]. In the second part we study theoretically the photonic spectrum of a bichromatic optical lattice extending the model of [3] and [4], in the regime in which the atoms are well localized in the lattice sites and their dipolar transitions couple weakly to the probe light. The photonic spectrum is characterized as a function of the interparticle distance D inside the primitive Wigner-Seitz cell. Depending on D and on the atomic species composing the Wigner-Seitz cell, two or more photonic bandgaps can be found. We then determine the dynamics, when the atoms couple to the standing-wave mode of a Fabry-Perot cavity, and study the cavity transmission spectrum in the strong coupling regime

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Laser cooling and trapping of atoms and molecules using nano-structured surfaces

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Trapping and cooling atoms and molecules allow studying their quantum nature with precision and coherence. Unfortunately many atoms and molecules lack fast closed optical cycles between their energy levels and as the result conventional optical cooling techniques become extremely complicated and inefficient.

We propose two related schemes for trapping and cooling of a wide range of atoms and molecules using micro-mirror arrays. For trapping we investigate micro-mirror trapping using the dipole force and micro-MOTs cooling and trapping using the scattering force. Having successfully trapped the species, micro-mirror mediated cooling [1] will be investigated using the same experimental setup. Mirror-mediated cooling, similar to cavity-mediated but using only a single mirror, uses the light's time delay between the particle and its mirror image to cool.

The spherical micro-mirror arrays can be grown using self-assembly electro-deposition techniques from 100μm diameter down to 0.1μm [2]. Traps based on such tiny mirrors have a number of advantages. With their high curvature and non-paraxial geometry they may couple to surface plasmon resonances which could enhance the light's focal density [3, 4] and delay time giving deeper traps and a more efficient mirror-mediated cooling. Furthermore the tiny dimensions of the traps mean that the trapped species are within wavelengths of the surface allowing evanescent field techniques [3] to be applied. Having an array of mirrors could collectively increase the distances and times over which the cooling process can occur.

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Inside nature's smallest blackbody

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Sonoluminescence is the intriguing phenomenon of strong light flashes from tiny bubbles in a liquid [1]. The bubbles are driven by an ultrasonic wave and need to be filled with noble gas atoms. Approximating the emitted light by blackbody radiation indicates very high temperatures [2]. Although sonoluminescence has been studied extensively, the origin of the sudden energy concentration within the bubble collapse phase is still controversial [3]. It is hence difficult to further increase the temperature inside the bubble for applications like sonochemistry and table top fusion.

Here we show that strongly-confined atomic systems can be heated very rapidly by a weak but highly inhomogeneous electric field [4]. Such a field might occur naturally during rapid bubble deformations and establishes a coupling between the vibrational and the electronic states of the particles. This coupling is similar to the coupling which occurs in laser sideband cooling experiment with trapped atoms and ions. We predict sharp emission lines which correspond to optical transitions in atomic systems as they have indeed been found in actual sonoluminescence experiments [1, 3]. Moreover, our model suggests that it is possible to increase the temperature inside the bubble even further with the help of appropriate laser fields.

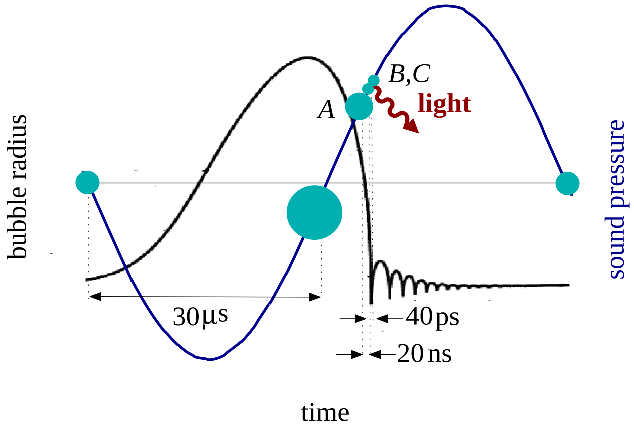

FIG. 1: A typical single-bubble sonoluminescence cycle showing the time dependence of the bubble radius and the driving sound pressure.

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Excess noise depletion of a Bose-Einstein condensate in an optical cavity

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Quantum fluctuations of a cavity field coupled into the motion of ultracold bosons can be strongly amplified by a mechanism analogous to the Petermann excess noise factor in lasers with unstable cavities. For a Bose-Einstein condensate in a stable optical resonator, the excess noise effect amounts to a significant depletion on long timescales. The cavity field induced depletion of a non-interacting condensate is calculated for two pumping geometries: For resonator pumping we reveal the main features of the excess noise depletion, while in the transverse pump geometry, where the condansate atoms are illuminated from the side, we explore how the depletion accompanies the spatial self-organization process.

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Cavity nonlinear optics with few photons and ultracold quantum particles

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The light force on particles trapped in the field of a high-Q cavity mode depends on the quantum state of field and particle. Different photon numbers generate different optical potentials and different motional states induce different field evolution. Even for neglible internal particle excitation, which yields linear polarizability, the quantumness of particle motion generates nonlinear field dynamics. We derive a corresponding effective field Hamiltonian containing all the powers of the photon number operator, which predicts nonlinear phase shifts and squeezing even at the few-photon level. Simulations of the full particle-field dynamics confirm this and show significant particle-field entanglement.

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Revealing anyonic features in a toric code quantum simulation

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Anyons are quasiparticles in two-dimensional systems that show statistical properties very distinct from those of bosons or fermions. While their isolated observation has not yet been achieved, we actually perform a quantum simulation of anyons on the toric code model [1]. By encoding the model in the multi-partite entangled state of polarized photons, we are able to demonstrate various manipulations of anyonic states and, in particular, their characteristic fractional statistics.

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