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Cavity quantum electrodynamics

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Abstract
The simplest model in quantum optics deals with a single two-level atom interacting with a single mode of the radiation field. This ideal situation is implemented in Cavity Quantum Electrodynamics experiments, using high quality microwave or optical cavities as photon boxes. It provides a test bench for fundamental quantum processes and a promising ground for quantum information processing.

Introduction
Most experiments dealing with matter-light interaction involve a large number of atoms interacting with laser fields made up of a large number of photons. The simplest situation,

however, involves a single atom interacting with one or a few photons. Achieving this situation is the aim of Cavity Quantum Electrodynamics (CQED) [1, 2].

The history of CQED started, more than 50 years ago, with a seminal remark by Purcell. The radiation properties of an atom can be changed by controlling the boundary conditions of the electromagnetic field with mirrors or cavities. CQED experiments initially measured modifications of spontaneous emission rates or spatial patterns in low-quality cavities. They evolved to higher and higher atom-cavity couplings and photon storage times. Most of them are now in the so-called regime of 'strong coupling', in which the coherent interaction of a single atom with one photon stored in a very-high-quality cavity, a modern equivalent of Einstein's photon box, overwhelms the incoherent dissipative processes.

CQED experiments implement a situation so simple that their results can be cast in terms of the fundamental postulates of quantum theory. They are thus appropriate for tests of basic quantum properties: quantum superposition, complementarity or entanglement. In the context of quantum information processing, the atom and the cavity are long-lived qubits, and their mutual interaction provides a controllable entanglement mechanism – an essential requirement for quantum computing or teleportation applications. CQED is therefore a fertile ground for quantum information processing. In addition, the ability to manipulate mesoscopic fields, containing a few to a few tens of photons, made it possible to explore the fuzzy boundary between the quantum and the classical worlds, unveiling the decoherence mechanisms that confine the quantum weirdness at a microscopic scale.

CQED comes in two flavours: microwave and optical. Both situations achieve the strong-coupling regime, with different and complementary features. In the microwave domain, very excited 'Rydberg' states interact with superconducting millimetre-wave cavities. Dissipation is very low, and the pace of the atom-field entanglement process is slow. An exquisite degree of control is reached, making it possible to tailor complex multi-qubit entangled states. In Europe, this line of research is mainly pursued by H. Walther in Munich, and S. Haroche with one of us (JMR) in Paris. In the optical domain, low-lying atomic levels interact with room-temperature optical cavities. The interaction is much faster, as is the dissipation. This, however, turns out to be an asset: optical photons can be efficiently coupled in or out of the cavity. Optical CQED thus provides a natural and essential interface between flying photonic qubits for the transmission of quantum information and stationary atomic qubits for the storage of quantum information. In Europe, this regime of CQED is studied by one of us (GR), while other groups are setting up new experiments.

This paper gives a short introduction into CQED. It highlights some recent achievements and discusses perspectives for quantum information processing opened up by the first experiments. More details and references can be found in [2 - 4].

Microwave Cavity Quantum Electrodynamics

In order to reach the strong coupling regime, a CQED experiment must combine large atom-field couplings with long atomic and field lifetimes. The longest photon storage times, in the 1 ms to 1 s range, are obtained in the millimetre-wave domain (few tens of GHz), with photon boxes made up of superconducting materials cooled down to cryogenic temperatures. They have sizes comparable to the wavelength and provide a high field confinement, essential to increase the atom-field coupling. Rydberg atoms, in which an alkali's valence electron is promoted to a level with a large principal quantum number N, are strongly coupled to microwaves. In particular, circular levels, realizing Bohr's orbit, have an extremely long lifetime (30 ms for $N = 50$). They can be detected in a selective and sensitive way by field ionization. They are ideal tools for cavity field manipulations.

Figure 1 presents the scheme of a CQED experiment with circular Rydberg atoms [5]. Laser and microwave excitation of an atomic beam, effusing from oven *O,* prepares in box *B* one of the states *e* or *g* (N=51 or N=50). Before entering *B*, the atoms are velocity-selected by laser techniques. The state preparation being pulsed and performed at a precise location, the position of an atom at any time during its transit through the apparatus is well determined. This is essential to ensure single qubit addressing. The atoms, very sensitive to microwave fields, are in a cryogenic environment, cooled below 1 K and shielded from the room temperature blackbody background. They interact with the superconducting cavity *C*, nearly resonant with the transition between *e* and *g* at 51 GHz. A static electric field applied across the cavity mirrors tunes the atomic transition in or out of resonance with *C*, via Stark effect. The atoms are finally detected in the field-ionization counter *D*, whose efficiency reaches 90%, providing a nearly ideal qubit read-out.

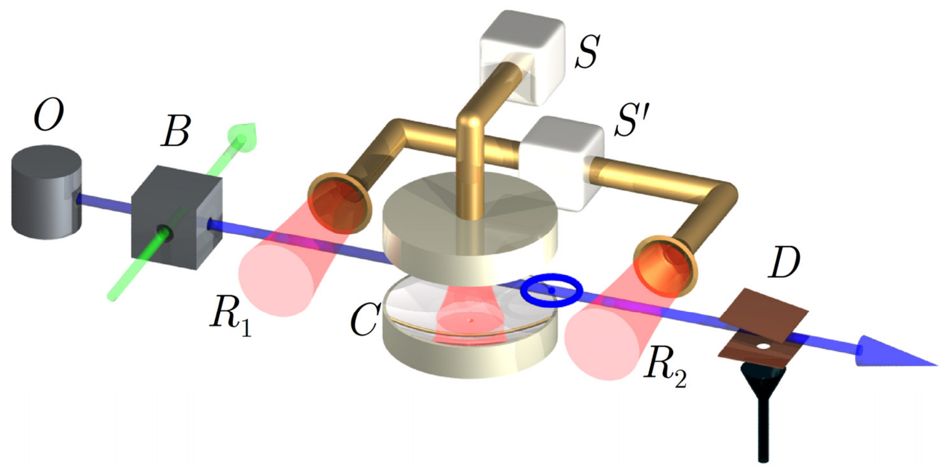

Figure 1 A classical source *S*, coupled to *C*, can be used to fill the cavity with a mesoscopic quasi-classical field. Another source *S'* feeds two interaction zones R_1 and R_2 sandwiching *C*. The resonant interaction of the atom with the classical field in these zones realizes single-qubit gates. The atom can thus be prepared in any state before entering *C*. The gate realized in R_2 before the final detection in the $\{e, g\}$ basis by *D*, makes it possible to analyse completely the final atomic state.

Most quantum entanglement manipulations realized so far rely on the resonant atom-cavity interaction. The simplest situation is an atom entering the empty resonant cavity in the upper state, *e*. The initial quantum state *e*,0 is degenerate with *g*,1 representing an atom in the lower state with one photon in the cavity. The atom-field dipole interaction couples these states and the atom-cavity system thus oscillates between them in a `vacuum Rabi oscillation'. Note that no evolution takes place when the initial state is *g*,0 (atom in the ground state and empty cavity) since there is no excitation to exchange.

Figure 2 presents an experimental vacuum Rabi oscillation. The probability P_e for detecting the atom in *e* is plotted as a function of the atom-cavity interaction time, t_i. The observation of four 20 μs periods shows that the coherent atom-cavity interaction dominates dissipative processes, fulfilling the strong coupling condition. This oscillation is a reversible spontaneous emission process. The atom in *e* emits a photon. When the emission occurs in free space, the photon escapes at light velocity and is lost. Ordinary spontaneous emission is irreversible.

Here, the emitted photon remains trapped in *C*, ready to be absorbed again by the atom. In the strong coupling regime, spontaneous emission is a reversible process!

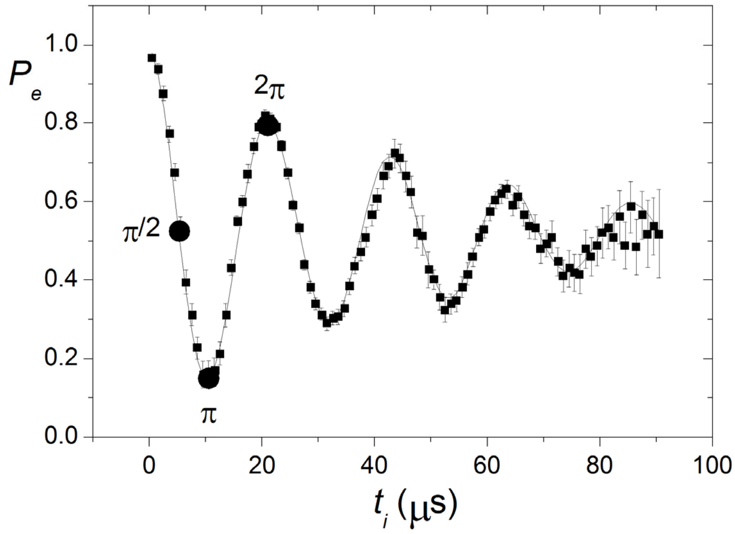

Figure 2

Oscillatory spontaneous emission is at the heart of an interesting quantum device, studied in the Munich group: the micromaser (see the Chapter by Raithel *et al.* in [1]). A stream of Rydberg atom crosses the cavity. Cumulative emissions build up a mesoscopic field. The cavity damping time is so long that the maser action is sustained even though the average time interval between atoms is much greater than their transit time through *C*. The micromaser operates with much less than a single excited atom at a time, a remarkable regime in which quantum effects are of paramount importance.

The vacuum Rabi oscillation provides elementary stitches to knit complex entangled states. Three atom-cavity interaction times are particularly interesting. They are depicted by black circles in **Figure 2**. At a quarter of a period, atom and cavity are in a coherent superposition of e,0 and g,1 with equal weights. This is an entangled state, similar to the one of the spin pair used to discuss the EPR (Einstein-Podolski-Rosen) situation, illustrating quantum non-locality. The atom-cavity entanglement lives as long as the photon in the cavity, about a millisecond. This time is much longer than the mere 5 μs required for its creation, allowing for complex sequences.

Half a period corresponds to an atom-cavity state exchange. An atom entering the empty cavity in a superposition of its energy states always ends up in g, leaving in *C* a coherent superposition of the zero- and one-photon states. In quantum information terms, the qubit carried by the atom is copied onto the cavity. The process is reversible. An atom entering C in the lower level g for a half-period interaction takes away the cavity state. This operation does not create entanglement, but is essential since the cavity field is not directly accessible here, in contrast with optical CQED situations.

Finally, a full Rabi oscillation period drives the atom-cavity system back to its initial state, albeit with a state sign change. The same phase shift occurs when the initial state is g,1, the atom transiently absorbing the photon and releasing it. Note again that g,0 remains invariant. The state sign change is thus conditioned to the state of the atom and of the cavity. It is a conditional coherent quantum dynamics, i.e. a quantum gate.

Combining these transformations, the ENS group has realized complex quantum information processing sequences [5]. In a quantum memory experiment, the state of a first atom is copied onto *C*, stored for a while, and later taken away by a second atom. An EPR atomic pair is created by entangling a first atom with *C* (quarter of a period interaction). The cavity state and, hence, its entanglement with the first atom is then copied onto a second atom. Quantum correlations between the atomic states assess the coherence of the process.

The most complex sequence realized so far is the creation of a three-qubit entangled state. The cavity is entangled with a first atom, as above. A second atom then comes in and realizes a quantum gate operation based on the full Rabi period. It gets entangled with *C* and, hence, with the first atom, completing the three-qubit entanglement. Quantum correlations between these qubits are then measured. A third atom is involved to read out the field state. Altogether, the production and analysis of this entanglement involves four qubits, three one-qubit gates and three two-qubit ones. It is among the most complex sequences realized with individually addressed qubits.

The entanglement fidelity is, above, mainly limited by cavity damping. Another type of quantum gate gets rid of this limitation. Two atoms, one in *e* and one in *g*, interact simultaneously with the non-resonant cavity. The first virtually emits a photon in *C*, immediately absorbed by the other. This cavity-induced coherent collision creates entanglement and provides gate dynamics. Since the photon is only virtually present, the process is not affected by cavity losses. It is very promising for quantum information processing with moderate quality cavities.

Another remarkable feature of these experiments is the ability to manipulate in *C* mesoscopic fields, made up of a few to a few tens of photons. Their interaction with a single atom is strong enough to put them in a mesoscopic quantum states superposition, for instance a superposition of two fields with different classical phases. These non-classical states bear a strong analogy with the famous Schrödinger cat, suspended between life and death in quantum limbs. The slow relaxation of the cavity makes it possible to study in 'real time' the decoherence mechanism [5] transforming the quantum superposition into a probabilistic alternative, the transition being faster and faster when the cat's size increases. These decoherence studies are important for fundamental quantum mechanics issues but also because decoherence is a serious obstacle on the road towards practical quantum computation.

Optical Cavity Quantum Electrodynamics

All CQED experiments can be described by three physically distinct time scales. One is the period of the oscillatory exchange of a single energy quantum between the atom and the cavity, the Rabi time, see **Figure 2**. A second time is the transit time of the atom through the cavity. The third time comes from the coupling of the combined atom-cavity system to the environment and is determined by the photon lifetime inside the cavity and the atomic lifetime due to spontaneous emission into directions not supported by the cavity.

In principle, these three times scales can be arbitrary, making the description of an experiment rather tedious. CQED, however, achieves the ideal situation in which these time scales can differ by orders of magnitude. The distinct hierarchy is the key ingredient for coherently controlling the system at the level of single atomic and photonic quanta. In the microwave domain, it ensures that different atoms passing the cavity one after the other interact with essentially the same cavity field. In the optical domain, the time scales follow a different hierarchy. While in the regime of strong coupling the single-photon Rabi period is still shorter than the lifetimes of both the cavity and the atom, the transit time can now be many orders of magnitude longer. It follows that a single atom can interact with literally thousands and millions of photons one after the other. This provides an excellent opportunity to make real-time measurements on a single atom by observing the photons emitted from the cavity. In fact, the rate of information one can achieve from a single intra-cavity atom can significantly exceed the corresponding rate of a free-space atom, for two reasons: one is the nearly 'one-dimensional' radiation environment, the other is the fast time scale provided by the short Rabi period in the regime of strong coupling. The loss of photons is therefore a highly useful ingredient of optical CQED experiments [6].

It follows, that atoms and photons play opposite roles in microwave and optical CQED. This can also be understood when comparing the kind of excitation that is typically employed to drive the atom-cavity system in the two domains. In most microwave experiments, energy is provided by atoms entering the cavity in the excited state, quickly depositing a photon into the cavity. In the optical domain, atoms tend to be in their ground state, and excitation of the system is provided by an external laser. Two configurations are possible: Firstly, the laser drives the atom which then emits a photon into the cavity, again by virtue of the short Rabi time in the strong coupling regime. Secondly, the laser excites the cavity whose transmission is modified by the presence of the atom. In both configurations, accurate knowledge about the atom can be obtained by observing with unprecedented time resolution the photons that escape the cavity through one (or both) of its mirrors.

Let us now look at a typical experiment as displayed in **Figure 3** [2]. Here, the cavity is of the Fabry-Perot type and consists of two concave dielectric mirrors facing each other at a distance of the order of a few 100 μm. In addition to a small cavity waist, the small distance between the mirrors is an essential requirement for achieving strong coupling. This can easily be explained by noting that the huge electric field (typically a few 100 V/m) of a photon confined to a small volume in space makes the interaction between the atom and the photon very large. The small mirror spacing, however, has a pronounced disadvantage: the photon lifetime is small, too. To compensate the decrease of the cavity lifetime, the reflectivity of the mirrors must be as high as possible. The best commercially available mirrors feature transmission, absorption and scattering losses down to about 1 : 1 000 000 each, a value several 10 000 times smaller than that of metallic mirrors. This makes it possible to realize cavities with a finesse of a few 100 000, meaning that single photons are reflected to and fro several 100 000 times.

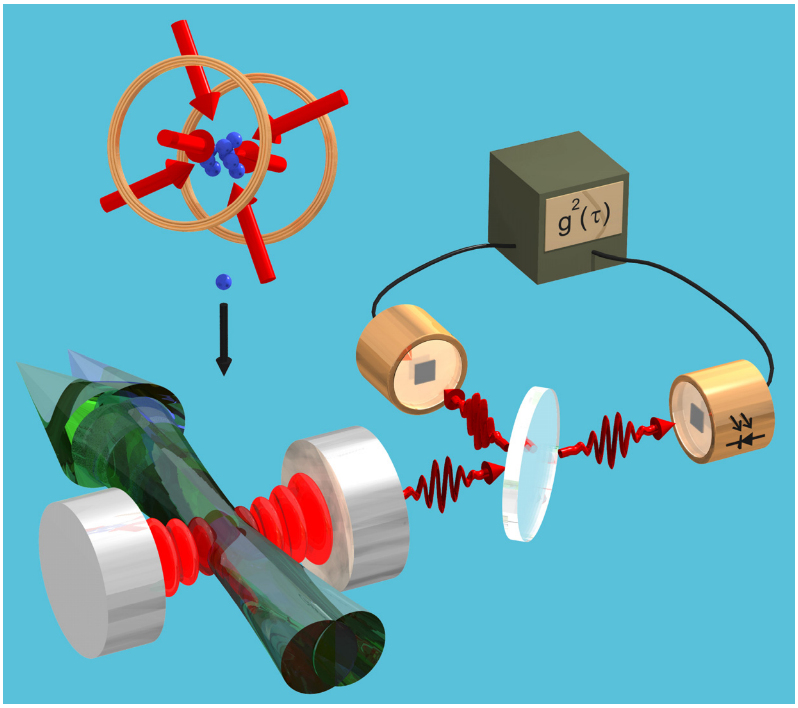

Figure 3

Single atoms are now sent between the two mirrors, either dropped from above or injected from below in fountain geometry. The velocity of the atoms is reduced to a value close to zero by standard laser cooling and trapping techniques. In the simplest situation, these atoms just pass the cavity in free fall, in which case transit times of the order of a few 10 μs are achieved. The atoms can also be trapped inside the cavity by means of an auxiliary laser field (not shown in **Figure 3**). In the latter case, single atoms have been observed to stay inside the cavity for many seconds, limited either by collisions with atoms of the background gas in a non-perfect vacuum or, ultimately, by the cavity-enhanced vacuum fluctuations of the trapping laser. The extended cavity dwell time, however, comes at the expense of a dramatically more complex protocol of capturing, trapping and cooling the intra-cavity atom. The precise control of the atomic motion between closely spaced, highly reflecting mirrors is subject of intense investigations in several laboratories worldwide.

Many spectacular CQED experiments have been performed in the optical domain during the last few years. These include the observation of single atoms in real-time, the vacuum-stimulated scattering of photons, the feedback on the atomic motion based on a velocity measurement, the cooling of atomic motion by means of a novel technique avoiding spontaneous emission, the realization of a continuously operated single-atom light source, the optical transport of single atoms through a high-finesse cavity, and the spectroscopic investigation of the energy-level structure of the strongly coupled system. But arguably most interesting from the point of view of quantum information processing is the demonstration of a novel light source emitting single photons on demand, as described now in more detail.

A novel feature of this new light source is that it generates photons without spontaneous emission. In particular, the emitting atom is at no time promoted to an excited state. Instead, the atom is always in a so-called dark state: By slowly varying the parameters of the system, the atom is adiabatically transferred from one ground state to another ground state (of another hyperfine or Zeeman level) while depositing a photon into the initially empty cavity. The process is intrinsically reversible and thus ideal to inter-convert flying and stationary qubits, i.e. photons and atoms, respectively. It also allows one to shape the time-dependent amplitude and phase of the emitted photon. Experimentally, the passage is achieved by slowly increasing the intensity of the laser driving the atom (see **Figure 3**) and simultaneously decreasing the strength of the atom-cavity coupling, e.g., by removing the atom from the cavity. The decrease of the atom-cavity coupling can alternatively be realized by employing cavity decay, i.e., by removing the photon from the system. In the latter case, the atom can be pumped back to the initial state and the whole process can be repeated as long as the atom resides in the cavity. In this way, a bit stream of single-photon pulses is generated.

Figure 4 shows data from the very first experiment [2] already performed in 2002 with atoms falling through the cavity at such a low rate that the probability of having two or more atoms in the cavity is negligible. The figure displays the intensity autocorrelation function of the emitted photon stream as measured with the Hanbury-Brown and Twiss setup of **Figure 3**. The pronounced peaks reflect the pulsed nature of the light source and occur at times determined by the repetition rate of the pump laser, about 200 kHz. The missing peak at zero delay time proofs that single photons are emitted, because single photons cannot hit simultaneously the two photon detectors behind the beam splitter. The decay of the peak height for increasing delay time comes from the finite atom-cavity transit time in this first experiment. The decay was largely suppressed in similar experiments performed recently with a trapped atom or ion. Exciting results were also obtained in an experiment in which two photons generated successively were appropriately delayed and superimposed on a beam splitter. A novel interference effect was observed that occurs only for quantum light fields. It proves that a CQED single-photon light source is ideal for quantum communications and quantum computing in a distributed network of atom-cavity systems, as proposed by several theory groups worldwide.

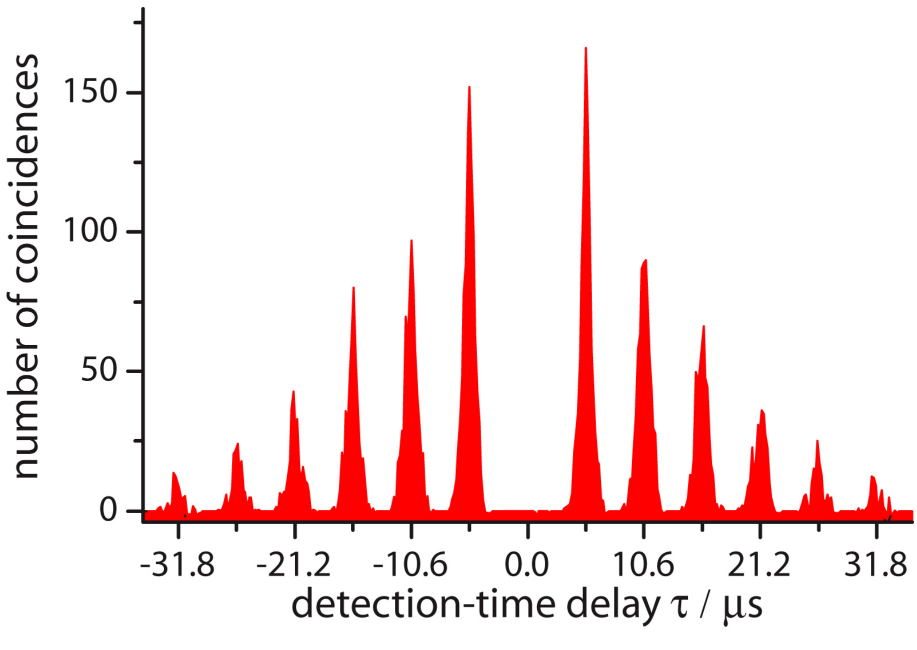

Figure 4

The experimental techniques required to control both the internal and external degrees of freedom of single strongly coupled atoms are quite demanding, making the experiments a true challenge. However, experimental progress has been impressive in the relatively young research field of optical CQED. From the theoretical side, the dissipative coupling to the environment makes the description of optical experiments very difficult. A big challenge is to take into account the atomic motion and the effect of the light force. This force arises from the recoil kicks the atom experiences when scattering a photon. The inclusion of the light force leads to a complex interplay between the motion of the atom, its internal dynamics and the dynamics of the cavity field. No general solutions of the problem of a driven, open system are known even for one intra-cavity atom.

Conclusions

Both in the microwave and the optical domains, more experiments in the same league as those mentioned above are now in progress or planned. For example, it will be possible to repeatedly move trapped atoms in and out of the strong-coupling region in the near future, enabling one to address individual or pairs of qubits of an atomic quantum register with a high-finesse cavity. Hence, deterministic entanglement of one stationary atom (out of many) and a flying photon is within sight. In another line of experiments, setups with two separated cavities are presently under construction. They will offer a much greater flexibility and new possibilities for quantum information processing. For example, atomic state teleportation at a macroscopic distance (several meters) seems to be in reach. Finally, non-local Schrödinger cat states could be created and studied. Such states are a completely new species of quantum monsters, putting our understanding of decoherence and non-locality under close scrutiny.

It is even possible to envision experiments blending atom chip and CQED concepts. On-chip conveyor belts can be used to transport atoms and move them into on-chip transmission-line cavities. Such integrated experiments provide a scalable architecture for quantum information processing. Coherence preserving traps can be tailored for Rydberg atoms, holding them over superconducting chips, which block their only decay, spontaneous emission. In addition, the on-chip atoms could be coupled with superconducting qubits also integrated on-chip, opening a wealth of new possibilities. Last but not least, the recent advances in nanotechnology will allow one to design novel wavelength-sized optical cavities, e.g., with photonic band gap materials. Such small cavities could dramatically boost the speed of quantum gates or the rate of single photons delivered on demand. A first step into this direction has already been done with the achievement of strong coupling in systems with artificial atoms, i.e. quantum dots. All these exciting possibilities give CQED a bright future!

List of terms and acronyms

CQED: Cavity Quantum Electrodynamics

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QUBITS
Quantum Based Information Processing and Transfer with Single Atoms and Photons
Start date: 01/01/2000
End date: 31/12/2002
Project web site: http://www.imperial.ac.uk/physics/qubits/
Contact Person: Peter Knight, Imperial College, London, UK, p.knight@ic.ac.uk

QUEST
Quantum entangled states of trapped particles
Start date: 01/05/2000
End date: 31/04/2004
Project web site: http://www.iota.u-psud.fr/~quest/index.html
Contact Person: Philippe Grangier, IOTA, Orsay, France, philippe.grangier@iota.u-psud.fr

QUIPROCONE
Quantum Information Processing & Communications Network of Excellence
Start date: 01/08/2000
End date: 31/07/2003
Project web site: http://www.quiprocone.org/quipmain.htm
Contact Person: Tim Spiller, Hewlett Packard, Bristol, UK, ts@hplb.hpl.hp.com

QGATES
Quantum Gates and Elementary Scalable Processors Using Deterministically Addressed Atoms
Start date: 01/01/2003
End date: 31/12/2005
Project web site: http://www.imperial.ac.uk/physics/qgates/
Contact Person: Danny Segal, Imperial College, London, UK, d.segal@ic.ac.uk

CONQUEST
Controlled quantum coherence and entanglement in sets of trapped particles
Start date: 01/03/2004
End date: 28/02/2008
Project web site: http://www.quniverse.sk/conquest/
Contact Person: Vladimir Buzek, Bratislava, Slovakia, buzek@savba.sk

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QIV
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Contact Person: Gerd Leuchs, Erlangen, Germany, leuchs@physik.uni-erlangen.de

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