Quantum Memory with a Single Photon in a Cavity

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The quantum information carried by a two-level atom was transferred to a high-Q cavity and, after a delay, to another atom. We realized in this way a quantum memory made of a field in a superposition of 0 and 1 photon Fock states. We measured the "holding time" of this memory corresponding to the decay of the field intensity or amplitude at the single photon level. This experiment implements a step essential for quantum information processing operations. [S0031-9007(97)03701-0]

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The manipulation of simple quantum systems interacting in a well-controlled environment is a very active field in quantum optics, with strong connections to the theory of quantum information [1]. Atoms and photons can be viewed as carriers of "quantum bits" (or qubits) storing and processing information in a nonclassical way. The interaction between two qubit carriers can model the operation of a quantum gate in which the evolution of one qubit is conditioned by the state of the other [2,3]. Combining a few qubits and gates could lead to the realization of simple quantum networks in which an "engineered entanglement" between the interacting qubits carriers could be achieved. Even if practical applications to large scale quantum computing are likely to remain inaccessible [4], fundamental tests of quantum theory could be performed, such as demonstrations of new quantum nonlocal effects [5], decoherence studies, etc.

Several quantum optics systems are investigated in this context, including trapped ions [6,7], combinations of photon pairs [8], or atoms in cavities [9]. In the latter case, atoms cross one at a time a high-Q cavity. The qubits are carried either by the atom, schematized as a two-level system, or by the quantum field in the cavity, which is in a superposition of 0 and 1 photon states. The interaction between the atom and the cavity field mode provides the conditional dynamics required for the operation of a quantum gate, as has been demonstrated recently in microwave [10] and in optical cavity QED experiments [11].

To implement quantum logic, the information should be transferable between qubit carriers and preserved between gate operations. This involves the existence of a quantum memory whose holding time is limited by the carrier relaxation processes. We report here the realization of a quantum memory in a cavity QED experiment. We have transferred a qubit from an atomic carrier to a field one, then to another atom. The initial atom was either in one of its two energy eigenstates, or in a superposition of them. The mediating field was prepared either in a 0 or 1 photon number state (Fock state) or in a superposition of the two. These are highly nonclassical states of radiation. By varying the delay between the two transfer processes, we have measured the qubit holding time of the cavity. We have directly determined in this way the lifetime of a single photon and of a superposition of 0 and 1 photon.

The principle of the quantum information transfer relies on the Rabi precession at frequency $\Omega/2\pi$ of an atom between two energy eigenstates e and g in the cavity vacuum $|0\rangle$ [12]. If the atom starts in the upper level e and the effective resonant atom-cavity interaction time t [12] is such that $\Omega t = \pi$, the combined system evolves from the $|e,0\rangle$ into the $|g,1\rangle$ state: the atomic excitation is transferred to the field. If the atom is initially in level g, the system starts in the $|g,0\rangle$ state and no evolution occurs. If the atom is initially in a superposition $\alpha|e\rangle + \beta|g\rangle$, the linearity of quantum mechanics implies that the combined system evolves into the state $(\alpha|1\rangle + \beta|0\rangle)|g\rangle$. The interaction has transferred the quantum superposition from the atom to the field, leaving the former in g. This information can then be transferred to a second atom initially in g and crossing the cavity after a delay, in a process reverse of the one experienced by the first atom.

The main elements of our setup, schematized in Fig. 1, have been described elsewhere [12,13]. Rubidium atoms

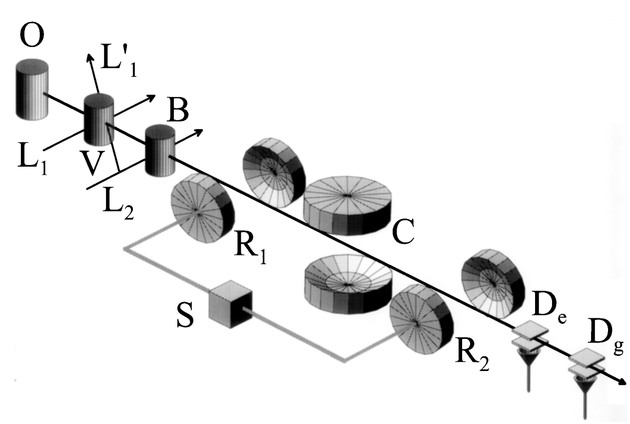

FIG. 1. Sketch of the experimental setup.

effusing from an oven O and velocity selected in zone V, are prepared in box B in the circular Rydberg state with principal quantum number 51 (level e) or 50 (level g) [14]. The atoms then cross a low-Q cavity R_1 in which a classical microwave pulse resonant with the transition at 51.1 GHz between e and g can be applied to prepare a controlled superposition of these two states.

The atoms then pass through a high-Q superconducting cavity C in which the Rabi precession in vacuum produces the quantum information transfer. The cavity, made of two niobium mirrors in a Fabry-Perot configuration (mirror separation 2.7 cm), sustains two orthogonally polarized TEM_{900} modes M_1 and M_2 with a spacing of 70 kHz. The vacuum Rabi frequency of the Rydberg atom at cavity center is $\Omega/2\pi = 48$ kHz for both modes [12]. The field energy damping times, measured by standard microwave techniques, are $T_r = 112\ \mu$s and 84 μs for M_1 and M_2, respectively. Both modes are close to resonance with the $e \rightarrow g$ transition. Either of them can be tuned in exact resonance by Stark shifting the atomic transition with the help of a time-varying electric field $F(t)$ applied across the gap between the cavity mirrors. When a mode is not exactly resonant, it has no effect on the evolution of the atomic populations in C. By proper adjustment of $F(t)$, one can induce an exact π pulse of the atom interacting either with M_1 or M_2. After leaving C, each atom crosses a second auxiliary cavity R_2, identical to R_1, which can mix again e and g. Finally the atoms are detected by state-selective field ionization in detectors D_e and D_g for levels e and g, respectively (detection efficiency: 35%). The combination of R_2 and $D_{e,g}$ analyzes either the atomic energy (no pulse applied in R_2) or the quantum coherence between levels e and g (pulse applied in R_2). The distances between the exit of B and the centers of R_1, C, and R_2 are 5.4, 9.95, and 14.5 cm, respectively. The zone from B to D is cooled to 0.6 K by a ^{3}He-^{4}He refrigerator to avoid blackbody radiation (0.02 thermal photon on the average in C).

The control of the atomic velocity and of the atomic timing across the setup are essential. The velocity selection involves the optical depumping of the $F = 3$ ground hyperfine sublevel of rubidium with a diode laser L_1, followed by a Doppler selective repumping of this level with the help of a laser beam L_1' oriented at an angle with the atomic beam. By tuning the frequency of L_1', a velocity profile centered at 400 m/s with a ± 30 m/s width is selected in the Maxwellian distribution of the atomic beam. L_1' is pulsed with a 2 μs duration. The circular state preparation in box B is a pulsed process starting from the $F = 3$ hyperfine level which involves a stepwise excitation (lasers L_2) and radio frequency transitions. It prepares within a time window of 2 μs a pulse of velocity selected atoms in e or g. The circularization process cuts a very thin slice of ± 0.4 m/s in the already selected atomic velocity profile. This velocity selection procedure is checked by time-of-flight measurements. The position of each atom can thus be determined at any time between preparation and detection with a precision better than 1 mm. This allows us to fire microwave pulses in R_1 and R_2 and the Stark-switching field in C exactly when the atom reaches the corresponding position with the possibility of exposing successive atoms to different interactions. The intensity of the lasers L_2 is reduced so that about 0.3 atom on the average is prepared in each pulse, and the probability to have more than one atom is small.

A quantum information transfer sequence consists in sending from B a pair of atomic pulses with variable velocities separated by an adjustable delay. In 1% of the sequences, one atom is detected in each pulse (useful events). The atomic interactions with C are separated by a known delay T which is adjusted between 30 and 400 μs. The state of the two atoms are detected by D_e and D_g. The sequence is repeated every 1.75 ms, and statistics are accumulated to reconstruct the joint probabilities P_{ee}, P_{eg}, P_{ge}, and P_{gg} that the pair of atoms is found in any configuration of quantum states.

In a first experiment, we prepare a single photon Fock state and exchange energy between the two atoms of each pair. No state mixing pulses are applied in R_1 or R_2. The first atom is prepared in e, the second in g. Both are coupled to the same C mode (either M_1 or M_2) and undergo a π pulse. Ideally, if the pulses were perfect and the cavity Q infinite, the first atom would emit exactly one photon which would be picked up with unit probability by the second atom. As a result, the conditional probability to detect the second atom in e provided the first one is detected in g, $\Pi_{ge} = P_{ge}/(P_{ge} + P_{gg})$, should be exactly one. When cavity relaxation is taken into account, Π_{ge} is expected to decay exponentially with the time constant T_r.

Figure 2 shows the measured Π_{ge} probability as a function of the delay T between the atoms in units of T_r. Each point averages 7000 useful events. Data corresponding to the two cavity modes have been merged. The experimental points fit to an exponential curve displaying the decay of a single photon in the cavity with the expected rate $1/T_r$. The maximum probability extrapolated to zero delay is 74%. Several experimental imperfections explain this reduced value. The vacuum Rabi pulse in C cannot transfer more than 94% of the atoms, due to coupling dispersions related to the atomic position spread in the cavity mode. When an atom is detected, there is also a 20% probability to have a second atom in the pulse which may be undetected. Finally, an atom in g is erroneously counted by D_e in 13% of the cases (and an atom in e by D_g in 10% of the cases). This last point explains the 13% background at long times in Fig. 2. Taking all these effects into account, we get a maximum conditional probability at $T = 0$ of 70%, in good agreement with the observed value.

In a second experiment, we perform a transfer of coherence between the two atoms. The first one is prepared in

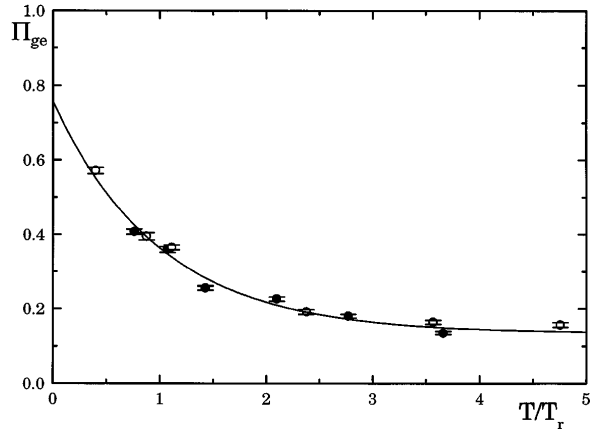

FIG. 2. Decay of a one photon Fock state in the cavity: conditional probability $\Pi_{ge}(T)$ versus the delay T between the two atoms expressed in units of cavity mode damping times T_r. Solid and open circles correspond, respectively, to a photon stored in mode M_1 ($T_r = 112\ \mu$s) or M_2 ($T_r = 84\ \mu$s). The line is an exponential fit with unit time constant and a 13% offset accounting for atomic energy detection errors.

e, undergoes a $\pi/2$ pulse in R_1, and is thus injected in C in a superposition $(|e\rangle + |g\rangle)/\sqrt{2}$. A π pulse in C transfers this coherence to the field (superposition of 0 and 1 photon states) and the first atom is finally detected in g. The second atom, prepared in g, experiences no pulse in R_1 and a π pulse in C. It enters thus R_2 in a coherent superposition of e and g. A $\pi/2$ pulse applied in R_2 analyzes the transferred quantum coherence. The conditional probability Π_{ge}, measured as a function of the common frequency ν of the microwave fields applied to the cavities R_1 (first atom) and R_2 (second atom), exhibits fringes which reveal the transfer of coherence. The signal is shown in Figs. 3(a), 3(b), and 3(c) for various values of the delay T between the two atoms. Each scan corresponds to 9000 useful events.

These recordings are reminiscent of Ramsey separated oscillatory field signals [15], the fringe period corresponding to the inverse of the time delay T' between the two interactions in R_1 and R_2. Here, however, the separated fields are applied to two different atoms. From the selected atomic velocities and the R_1 to C and C to R_2 distances, we get $T' = T + 216\ \mu$s. As a test of the consistency of our results, we have checked that the probability of detecting the second atom in e or g is independent of ν when the first atom is not sent in the apparatus.

Alternatively, one may see this experiment as the preparation of a nonclassical field in C, a superposition state with equal weights of 0 and 1 photon. Such a state, like a coherent one, has a nonzero expectation value of the electric field. It is different, however, from a coherent state, since it does not have a Poisson photon number distribution.

The fringe amplitude in Fig. 3 shrinks when the delay T is increased, measuring the decay of the coherence

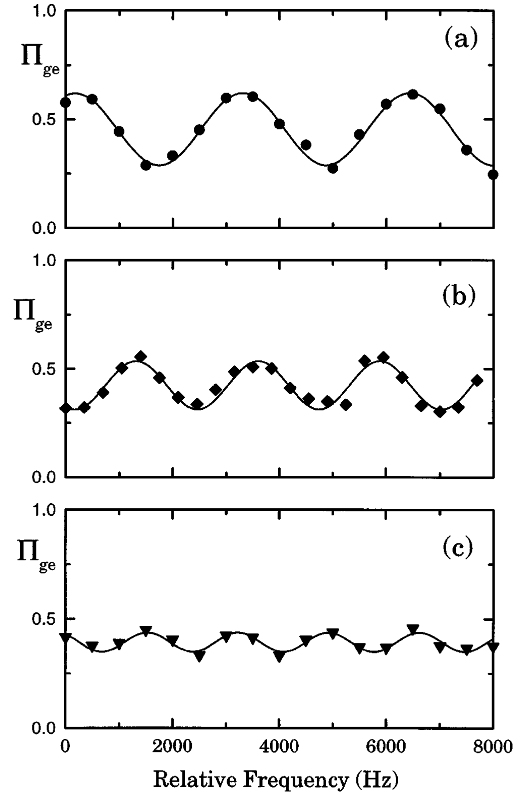

FIG. 3. Transfer of coherence between two atoms: conditional probability $\Pi_{ge}(\nu)$ versus the frequency ν of the microwave pulses applied to the first atom in R_1 and to the second in R_2. The delays $T' = T + 216\ \mu$s between the two microwave pulses in R_1 and R_2 are 301, 436, and 581 μs, respectively from (a) to (c). Cavity mode M_1 is used.

stored in the cavity field. Figure 4 shows this decay as a function of T/T_r. The experimental points fit now to an exponential with a characteristic time $2T_r$. The coherence between the 0 and 1 photon states lives twice

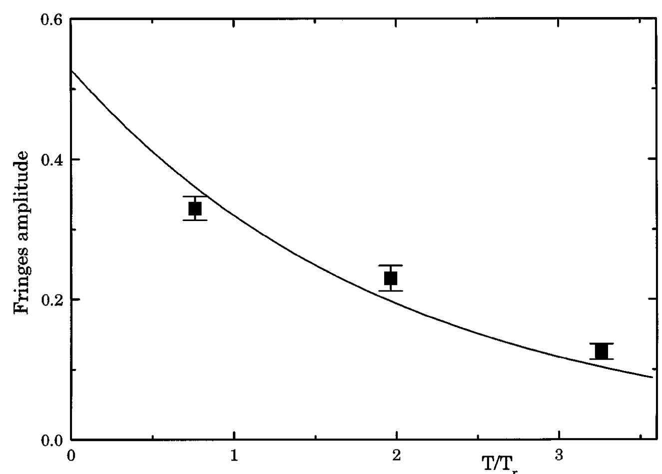

FIG. 4. Decay of the cavity field coherence: amplitudes of the $\Pi_{ge}(\nu)$ fringes of Fig. 3 versus the delay T expressed in units of $T_r = 112\ \mu$s. Solid line: exponential curve with a time constant of 2.

as long as a single photon. We are, in fact, measuring the average decay rate of a 1 photon state (rate $1/T_r$) and of the vacuum (rate 0). We can also remark that this experiment measures the field amplitude in C, whereas the previous one was measuring the field intensity. The maximum contrast value extrapolated to $T = 0$ (52%) derives from the single atom Ramsey fringes contrast (65%) by taking into account the various experimental imperfections discussed above.

This experiment shows that it is possible, via resonant atom-field interaction, to prepare and measure in a cavity a single-photon microwave quantum field which can serve as a mediator to transfer quantum information between two atoms. We thus realize a quantum memory which will be useful for further quantum information processing experiments. The blueprint for the realization of a cavity QED quantum gate [3] entangling a control and a target atomic qubit requires a transfer of the control qubit to the cavity field. This field is then coupled dispersively to the target atomic qubit and conditions its evolution, before being finally transferred back to a third atom, leaving the cavity empty. The exchange of information demonstrated in the present work plays an essential role in this program.

Combining a few gates to perform simple quantum logic operations is very challenging. This requires in particular a much better control of decoherence processes. With the improvements of the cavity modes quality factor under way in our laboratory, holding times 10 to 100 times longer than in this demonstration experiment could be obtained, opening the way to entanglement studies involving several atoms.

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