Simple cavity-QED two-bit universal quantum logic gate: The principle and expected performances

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We present a simple scheme for a universal two-bit quantum logic gate using circular Rydberg atoms and a superconducting millimeter-wave cavity. We analyze in detail the performances of this gate, using the parameters of an experiment currently under way in our laboratory.

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A computer which would manipulate quantum objects (q bits) as the elementary information carriers could take benefit of the superposition principle to achieve "massive parallelism." A prototype of such a computer is the "quantum Turing machine" [1]. This machine could solve some problems exponentially faster than any classical computer [2,3]. In particular, it has recently been shown [4] that the factorization of large integers can be performed on a quantum Turing machine in a "polynomial" time (polynomial function of the number of bits). This problem is believed to be complex for classical computers, since the best known algorithm takes a subexponential time [5]. The security of many cryptographic systems relies therefore on the difficulty of factorizing a large integer. The possibility of performing this factorization in a reasonable time triggered intense theoretical activity in the quantum computing field.

Though a quantum Turing machine could in principle perform any calculation, its architecture is clearly not an optimal one. It has been shown [6] that, for any computation, this machine can be replaced by a network of elementary processing units known as "quantum gates." These gates are analogous to standard logic gates used in classical computer construction. They are small "computing machines" having a fixed number of input and output "bits" and performing a fixed computation independent of the input. Instead of manipulating binary values (0 and 1), these gates perform a unitary, reversible transformation on two-level q bits (levels $|0\rangle$ and $|1\rangle$). Each q bit can be in any linear superposition of these two states. A "universal gate" is such that it can be used to build any computing network. Deutsch [6] proposed a universal three-bit gate derived from the Toffoli [7] logic gate. DiVincenzo [8] showed later that this three-bit gate can be implemented by an arrangement of two-bit gates. Sleator and Weinfurter [9], and, independently, Barenco [10], showed then that a two-bit gate is universal. Finally, it has even been shown [11] that any nontrivial two-bit gate is indeed universal.

We will consider in the following a two-bit transformation represented in the "computational basis" $|0\rangle=|0,0\rangle;|1\rangle=|0,1\rangle;|2\rangle=|1,0\rangle;|3\rangle=|1,1\rangle$, the direct product of the two-q-bits basis, by the unitary matrix

$$U=\begin{pmatrix} 1 & 0 \\ 0 & V \end{pmatrix} , \tag{1}$$

with

$$V=\begin{pmatrix} \cos\varphi & e^{-i\theta}\sin\varphi \\ -e^{i\theta}\sin\varphi & \cos\varphi \end{pmatrix} . \tag{2}$$

The two-bit gates considered in the previous literature can be easily recovered by combining U with a transformation represented by a diagonal unitary matrix made of mere phase factors. As we will see at the end of this paper, such a diagonal unitary transformation can be trivially implemented in the proposed scheme and will be discarded first.

The transformation U leaves the first q bit invariant. When this "control bit" is in state $|0\rangle$, the other one is also invariant. When the control bit is in state $|1\rangle$, the controlled bit experiences a unitary transformation described by the 2×2 matrix V (see Fig. 1). Note that, when the control q bit is initially in a superposition of states $|0\rangle$ and $|1\rangle$, the output states of the two q bits are entangled. Most of the fascinating features of quantum mechanics, like nonlocality and nonseparability, are therefore at the heart of the quantum computing process. For $\theta=-\pi/2,\varphi=\pi/2$, this gate, besides a common phase factor on the off-diagonal elements, reduces

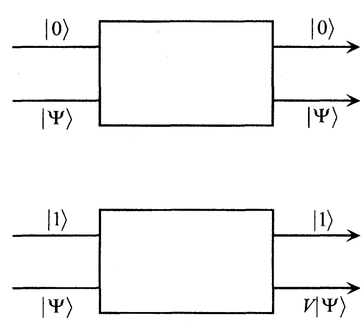

FIG. 1. Principle of a two-bit universal quantum logic gate. When the "control bit" (upper line) is in state $|0\rangle$, the other (lower line) is unchanged. When the control bit is in state $|1\rangle$, the other experiences a unitary transformation represented by the matrix V. For an arbitrary input, the two q bits exit the gate in an entangled state.

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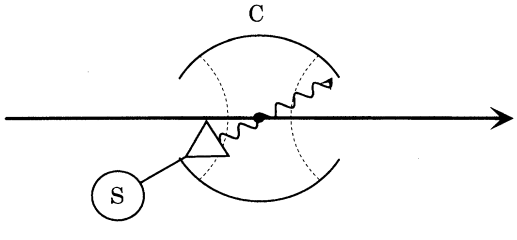

FIG. 2. Scheme of the cavity-QED two-bit gate. The control q bit is the state of a superconducting cavity C, either empty or containing one photon. The controlled bit is carried by a two-level circular Rydberg atom, slightly detuned from the cavity frequency. The state of the atom is manipulated by a classical field source S. The atom interacts noticeably with S only if the single photon field in C light shifts the transition in resonance with S.

to the so-called "measurement gate" or "controlled not" [12] and can be used for quantum state swapping [13] or teleportation [14,15].

The quantum computational networks put serious constraints on the experimental implementation, since all the quantum coherences should be maintained during the computation. This implies that the relaxation of the network due to its coupling to the outside world should be extremely low. Various possible implementations of universal two-bit gates with low relaxation systems have been proposed. Nuclear spin could be used to carry the information [8], but the realization would be extremely difficult in the present state of the art. A scheme using trapped ions has also been recently proposed [16]. The very small relaxation rates in Paul traps make a practical realization foreseeable though the experiment, involving very strong laser cooling of the ion motion, would certainly be a difficult one.

Cavity quantum electrodynamics [17] also provides situations where the coherent evolution overwhelms the dissipative processes. It has been recognized recently [13,12] that a quantum nondemolition measurement of a cavity field intensity at the photon level using atomic interferometry techniques [18] is a realization of the measurement, or controlled-not, gate. Recent elaborations [9] have shown that the parameters of the Ramsey interferometer can be tuned to produce a universal gate transformation. We present in this paper a simpler version of a cavity-QED two-bit gate which does not make use of the Ramsey technique. Instead, the light shifts experienced by the atomic levels in a superconducting cavity are used to control the coupling of the atom to a classical field performing the required transformation. We discuss the quality of the gate performance and the influence of the cavity and atomic relaxation processes with the orders of magnitude of an experiment under way in our laboratory [19].

Let us first, for the sake of clarity, describe an experiment where the control q bit is represented by the state of the cavity mode and where the control bit is carried by a two-level Rydberg atom (the case where both q bits are carried by atoms adds only technicalities to the principle described here and will be discussed later). The scheme of the proposed experiment is sketched in Fig. 2. The high-Q superconducting millimeter-wave cavity C either is empty or contains a single photon, these states representing respectively the

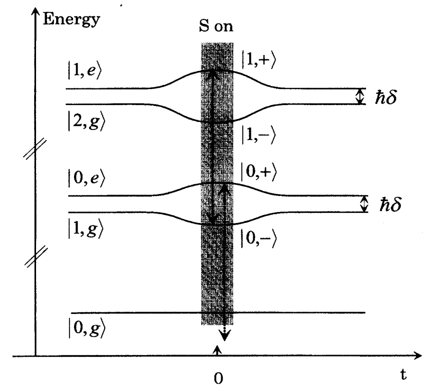

FIG. 3. Position of the atom-cavity energy levels ("dressed levels") as a function of time. The atom is on cavity axis at $t=0$. The classical source S is switched on during a small time interval around $t=0$. It is resonant with the transition between the dressed states $|0,-\rangle$ (originating from $|1,g\rangle$) and $|1,+\rangle$ (originating from $|1,e\rangle$) (solid arrow). It is therefore out of resonance on the transition between the state $|0,g\rangle$ (not affected by the atom-field coupling) and $|0,+\rangle$ (dashed arrow).

states $|0\rangle$ and $|1\rangle$ of the control q bit. We consider here a Fabry-Pérot type cavity, with a Gaussian transverse beam profile (waist $w=5.96$ mm). The experimental values of the field energy damping time $t_{\rm cav}$ for such cavities range from 1 to 30 ms. The other "controlled" q bit is carried by a "circular" Rydberg atom [20]. The state $|1\rangle$ is represented by a Rydberg level $|e\rangle$, while state $|0\rangle$ is represented by another, less excited level $|g\rangle$. The radiative lifetime of such levels, with a principal quantum number of the order of 50, is also in the 30 ms range. The cavity and atomic lifetimes are thus long enough to complete the required operation before the disturbing effects of relaxation could play an important role. To be more specific, we consider in the following the two circular levels of rubidium with principal quantum numbers 51 and 50. The $|e\rangle \rightarrow |g\rangle$ transition at frequency $\omega_0/2\pi=51.099$ GHz is quasiresonant with the cavity mode at frequency $\omega/2\pi$. The atom-cavity frequency mismatch $\delta=\omega_0-\omega$ is assumed to be small compared to the frequencies, but large compared both to the atom-field coupling (measured by the Rabi frequency in a single photon field at cavity center $2\Omega/2\pi \simeq 50$ kHz) and to the reciprocal of the atomic transit time across the cavity mode waist $t_{\rm trans}$.

The controlled q bit should undergo, during its interaction with the cavity, a dynamics conditioned by the occupation number of the cavity mode. The circular Rydberg atom is manipulated by an auxiliary classical millimeter-wave field, radiated in a transverse mode not belonging to the cavity by an auxiliary source S (see Fig. 2). The effect of the auxiliary field depends upon the state of the field in the cavity C, the control making use of the light shifts experienced by the atomic levels in the cavity field. Figure 3 sketches the atom-field energy levels as a function of the position of the atom along its path across the cavity mode, i.e., as a function of time. The ground state of the system is $|0,g\rangle$ representing an atom in $|g\rangle$ in an empty cavity. This state is not sensitive to the atom-cavity coupling. The more excited uncoupled atom–cavity energy levels are paired in nearly degenerate manifolds $\{|n,e\rangle,|n+1,g\rangle\}$ (the energy difference between

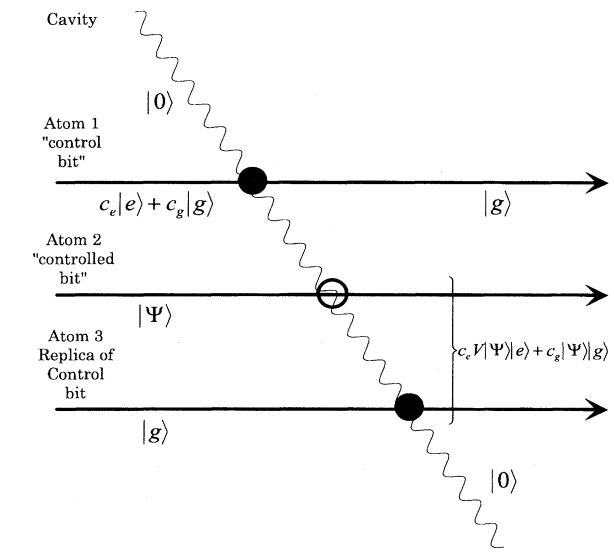

FIG. 4. Scheme of the quantum gate using only atoms as the q-bit carriers. The first atom's state is copied onto the cavity state through a resonant interaction depicted by a solid black circle. The second atom experiences a nonresonant interaction (open circle) and undergoes the required conditional dynamics. A third atom, interacting resonantly again with the cavity, carries away a replica of the first atom's state and leaves the cavity empty. The atom–cavity resonance condition is changed by applying a dc voltage between the superconducting cavity mirrors.

these levels being $\hbar\delta$). Inside the cavity, these levels are coupled by photon emission or absorption. They are mixed into the "dressed states" of the atom-field system $|n,+\rangle$ and $|n,-\rangle$. The energy splitting between $|n,+\rangle$ (originating from $|n,e\rangle$) and $|n,-\rangle$ (originating from $|n+1,g\rangle$) therefore increases with the atom-field coupling. This energy level modification, proportional to the excitation number, i.e., to the field intensity when $\delta \gg \Omega$, corresponds, for the atom, to the few-photons limit of the usual light shifts. If the atomic motion through the cavity is slow enough, the system will follow adiabatically the dressed energy levels. The photon number in C is therefore unchanged after the interaction, a clear consequence of the nonresonant nature of the atom-cavity interaction.

The classical field radiated by S is tuned into resonance with the $|1,+\rangle \leftrightarrow |0,-\rangle$ transition when the atom is close to the cavity axis. Note that this field, not directly coupled to the cavity mode, cannot change the photon number in C. An atom entering in C when it contains one photon will therefore enter in resonance with S and undergo a Rabi pulse whose area and phase can be controlled at will by a proper setting of the amplitude and phase of S. At variance, S remains off resonant in the case of an empty cavity, since it is far from resonance on the $|0,+\rangle \leftrightarrow |g,0\rangle$ transition. Any conditional unitary transformation of the atomic q bit [see Eqs. (1) and (2)] can thus, in principle, be realized.

The implementation of the gate with Rydberg atoms as the only q-bits carriers uses three atoms crossing successively the cavity as depicted schematically in Fig. 4. The first control q bit is carried by an atom in state $c_e|e\rangle + c_g|g\rangle$. This atom crosses the initially empty cavity mode. Using the Stark effect in a static electric field applied between the cavity mirrors, this atom can be tuned in exact resonance with C for a controlled amount of time. This interaction time is adjusted so that the atom experiences, when in state $|e\rangle$, an exact π pulse and releases one photon in the cavity, while it is not affected if initially in state $|g\rangle$. The interaction amounts then to the transformation

$$|0\rangle(c_e|e\rangle + c_g|g\rangle) \rightarrow (-ic_e|1\rangle + c_g|0\rangle)|g\rangle \tag{3}$$

performing, within trivial phase factors, an exact copy of the atomic state onto the cavity one [15]. Note that an entanglement of the first atom with another quantum system (which should be present in any multigate quantum computer) is also transferred to the cavity state. The "controlled" atom crosses then the nonresonant cavity. It experiences the conditional dynamics described above. The state of the cavity field is then copied back onto a third atom entering C in state $|g\rangle$, tuned to exact resonance with the help of a controlled Stark effect, and undergoing the inverse of transformation (3). The third atom exits C in a state which is an exact replica of the initial state of the control bit (including possible entanglement with other parts of the setup). The cavity is left empty, and could immediately be used for another cycle of the gate. Note that the first atom, which exited C in state $|g\rangle$, could in principle be used to carry away the control bit by recycling it again through the cavity, in an atomic fountain design (it is only a matter of experimental convenience to use a third atom). The interaction between the two atomic q bits could then be viewed as a collision process, mediated by the interaction with the same cavity field.

Let us discuss now the orders of magnitude of the experimental parameters. As mentioned above, we assume that the atom follows adiabatically the dressed states depicted in Fig. 3. This adiabatic approximation holds when the atom moves slowly enough and when the frequency mismatch δ is large compared to the coupling Ω to the cavity mode. The experiment is performed with velocity-selected atoms, prepared at a well defined time into the circular Rydberg state [20]. Their position at any time is therefore well known, and the classical field can be applied only during a time t_{int}, when the atoms are close to the cavity axis (see Fig. 3). This time selection improves considerably the performances of the gate by preventing unwanted transitions from occurring when the atom, outside the cavity, interacts with the detuned source. The variation of the dressed energy levels is small during t_{int} and will be neglected in this order of magnitude discussion. The auxiliary source S is resonant with the $|1,+\rangle \leftrightarrow |0,-\rangle$ transition at frequency

$$\omega_{rf} = \omega + \sqrt{\Omega^2 + \delta^2/4} + \sqrt{2\Omega^2 + \delta^2/4} \approx \omega_0 + 3\Omega^2/\delta \ , \tag{4}$$

where we have assumed $\delta \gg \Omega$. The atom–classical-field coupling is represented by the Rabi precession frequency $\Omega_{rf}/2\pi$, and can be adjusted by tuning the power of source S. The frequency mismatch Δ between this transition and S is

$$\Delta = \sqrt{2\Omega^2 + \delta^2/4} - \delta/2 \approx 2\Omega^2/\delta \ . \tag{5}$$

Some parameters (Ω, Q or t_{cav}, and the mode geometry represented by the waist w) are set by the experimental design, and cannot be adjusted at will during the experiment. Only four parameters can be tuned freely to optimize the gate characteristics: δ and the atomic velocity v as well as Ω_{rf} and t_{int}. Let us now examine the operating range for these adjustable parameters.

(i) Parasitic transitions are avoided when the coupling Ω_{rf} obeys the inequality

$$\Omega_{rf} \ll \Delta \quad . \tag{6}$$

(ii) The interaction time t_{int} must be shorter than the transit time $t_{trans} \simeq w/v$ across the cavity mode waist, so that the source is applied only when the atom is close to the cavity axis. This implies a frequency broadening of the transitions proportional to $1/t_{int}$ that must also be much less than Δ in order to resolve the $|g,0\rangle \leftrightarrow |0,+\rangle$ and $|1,+\rangle \leftrightarrow |0,-\rangle$ transitions:

$$\Delta t_{int} \gg 1 \quad . \tag{7}$$

(iii) The amplitude of the Rabi pulse, proportional to the product $\Omega_{rf} t_{int}$, should be tuned between 0 and π to realize any gate. Simultaneous fulfillment of this requirement and of condition (6) implies also that condition (7) is satisfied.

(iv) Condition (7), together with Eq. (5) implies low δ values. At variance, the adiabatic following of dressed states requires high detunings. A good compromise is found for $\delta = 2$ or $3 \times \Omega$.

(v) The atomic velocity should be low for the adiabatic conditions to be fulfilled. At the same time, the total experiment time should remain very short as compared to the relaxation time.

Numerically, we choose a velocity of 100 m/s, which can be easily selected by Doppler tuning of the Rydberg state preparation lasers. This velocity corresponds to a transit time $t_{trans} \approx 100$ μs across the cavity mode, and a total transit time across the whole setup around 0.5 ms. With $\delta/2\pi \approx 100$ kHz, we get $\Delta/2\pi$ values of the order of 15 kHz. These values being chosen once for all, only t_{int} and Ω_{rf} have to be adjusted for each gate. A minimal interaction time corresponding to a broadening of the order of Δ is in the 50 μs range. A π pulse corresponds then to $\Omega_{rf}/2\pi$ values of the order of 10 kHz. As a consequence, the preceding conditions can be only marginally fulfilled. A more rigorous analysis is necessary to see whether this logic gate operates as required.

This detailed analysis involves a numerical calculation of the system evolution. In order to check all the critical points of the experiment, this calculation does not make use of the adiabatic approximation. We integrate the Schrödinger equation in the basis of the uncoupled atom-field states. In addition to the four computational basis states, we have included the three states $|2,g\rangle$, $|2,e\rangle$, and $|3,g\rangle$. They allow us to describe correctly the possible nonadiabatic transitions as well as the thermal field effects. The motion of the atom through the cavity is treated classically, with a constant velocity. The depth of the potential well associated with the position-dependent dressed states [21] is much lower than the kinetic energy of the atoms. Hence the atom-cavity coupling has a negligible influence on the atomic motion. We have included atom and cavity field relaxation processes using the quantum Monte Carlo wave function method [22]. The system history is made of continuous evolution periods, under the action of a non-Hermitian Hamiltonian, suddenly interrupted by quantum jumps due to atom or field relaxation. Whenever a quantum jump appears in the evolution, we state that the operation is not successful, since any quantum coherence is lost. The cavity relaxation time used in the calculations is 16 ms, corresponding to $Q = 5 \times 10^9$ and the radiation temperature 0.7 K.

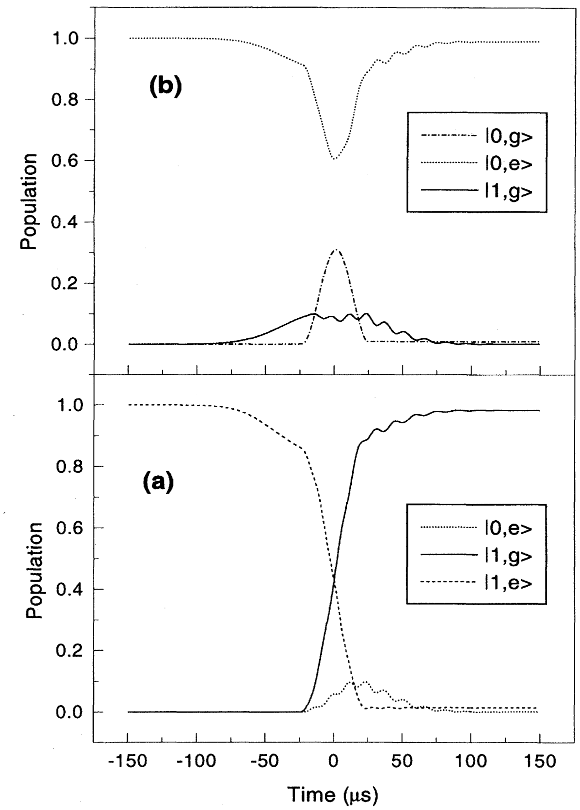

FIG. 5. Realization of a conditional π pulse on the atomic system. (a) Initial state $|1,e\rangle$. The transfer to state $|1,g\rangle$ is complete. (b) Initial state $|0,e\rangle$. After a transient admixture of other states, the system returns to the initial state. Interaction parameters are given in text.

We have optimized the parameters to obtain the required transformation with the best accuracy. Setting $\delta = 2\pi \times 62.5$ kHz and $v = 100$ m/s, the probability of a quantum jump during the 0.5 ms transit time across the whole apparatus is below 3%. Relaxation therefore plays a very small role only in the evolution of the system. The remaining adjustable parameters are Ω_{rf} and t_{int}. To obtain a π pulse (measurement gate) with the best accuracy, we have set $\Omega_{rf} = 2\pi \times 11.7$ kHz and $t_{int} = 47\mu s$. Figures 5(a) and 5(b) present the time evolution of the relevant states populations when no quantum jump occurs, for a system intially in states $|1,e\rangle$ and $|0,e\rangle$, respectively. The time origin in these figures corresponds to the cavity axis crossing. Between $t \approx -100$ μs and $t \approx 100$ μs, the atom is efficiently coupled to the cavity mode. In this time interval, one can distinguish two types of evolution. When source S is off, the system follows adiabatically the dressed energy states, which results in a small admixture of the uncoupled levels. The adiabaticity of this evolution supports the validity of the qualitative discussions given above. During the time when S is switched on (from $t=-23.5$ to $t=23.5$ μs), the populations of the two resonant levels evolve rapidly. The adjustable parameters are chosen so that state $|1,e\rangle$ is efficiently transferred to state $|1,g\rangle$ [see Fig. 5(a)] while a system prepared in state $|0,e\rangle$ returns quite precisely to $|0,e\rangle$ after a transient admixture with state $|0,g\rangle$ [see Fig. 5(b)]. This rather large admixture is due to the fact that condition (6) is only marginally fulfilled (there is only a factor of 2 difference between Ω_{rf} and Δ). We get rid of these parasitic transitions by a proper adjustment of experimental parameters. They are chosen so that the effective Rabi frequency on the $|0,+\rangle \leftrightarrow |0,g\rangle$ detuned transition is nearly twice the one on the resonant $|+,1\rangle \leftrightarrow |0,-\rangle$ transition. The second one experiences a π pulse, while the first one experiences a complete rotation, returning to the initial state. The quality of the gate can be measured by the probabilities of transition between the computational basis states, provided no quantum jump occurred in the evolution. The maximum deviation from the required values (squares of the moduli of the elements of U) is found to be of the order of 1.5%, comparable to the probability of a quantum jump.

An arbitrary pulse amplitude can be achieved by decreasing Ω_{rf} and adjusting slightly t_{int} (keeping the atomic velocity and the atom-cavity detuning fixed). For example, the temporal behavior of the $\pi/2$ gate ($\Omega_{rf}=2\pi\times5.46$ kHz and $t_{\mathrm{int}}=53$ μs) is depicted in Figs. 6(a) (initial state $|1,e\rangle$) and 6(b) (initial state $|0,e\rangle$). The transition probabilities for this gate deviate from the required values by less than 1%. The above figures clearly demonstrate that the gate operates quite satisfactorily even if the conditions raised by a qualitative analysis are only marginally fulfilled.

In a quantum computation, the phases of the complex amplitudes play a very important role and should be controlled accurately. The diagonal elements of the unitary transformation realized by this system are affected by phase factors. These factors result from the integrated atom-cavity level shifts. For instance, the state $|0,e\rangle$, which should not be affected by the gate, and though it stays nonresonant with S, experiences a shift in the cavity mode depicted in Fig. 3. One can easily adjust those phase factors to get, within an irrelevant global phase, the required universal transformation by tuning the phase of the two atomic q bits leaving the experiment. Differential Stark and Zeeman effects can be applied for well controlled amounts of time separately to the two atoms. They allow the experimenters to control the phases of the coefficients in the atomic states, without affecting the entanglement between the two atomic systems. Once this trivial phase compensation is performed, the phase of the nonvanishing nondiagonal elements of the realized unitary matrix [corresponding to θ in Eq. (1)] can be adjusted through the phase of source S. We have checked that it depends linearly on the phase of S, and very weakly only on its intensity, and can therefore be controlled with precision.

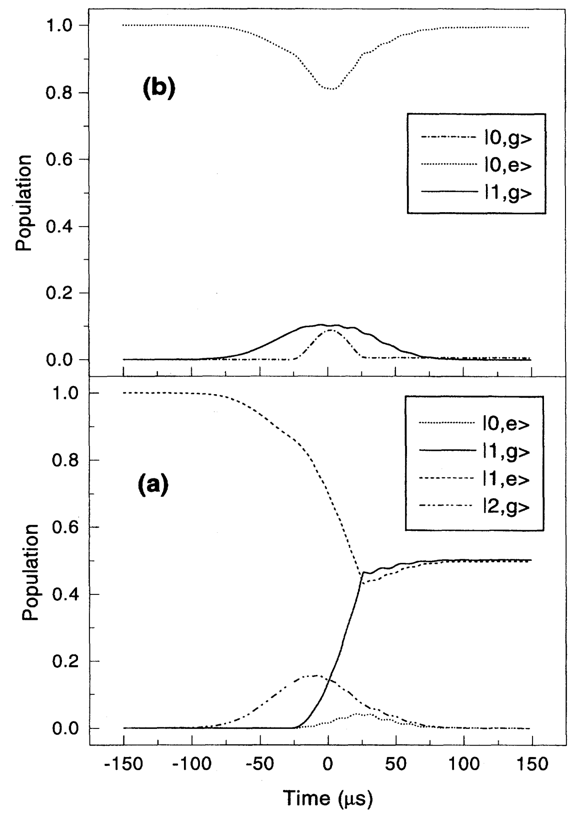

FIG. 6. Realization of a conditional $\pi/2$ pulse on the atomic system. (a) Initial state $|1,e\rangle$. At the end of the evolution, the system is in a superposition of $|1,e\rangle$ and $|1,g\rangle$ with equal weights. (b) Initial state $|0,e\rangle$. After a transient admixture of other states, the system returns to the initial state. Interaction parameters are given in text.

We have demonstrated here that an excellent approximation of the universal two-bit gate can be realized with a very simple cavity-QED experimental arrangement. The conditional transformation performed on the atomic q bit can be tailored at will through a proper adjustment of the experiment. The parameters are the ones of an experiment currently under progress in our laboratory. An effective realization of the gate is thus clearly feasible. The realization of a large-scale network able to perform a complex calculation such as a factorization is certainly much more difficult. The calculation time should be much less than the decoherence one, which is much shorter than the relaxation time for an individual gate [23]. This puts very strong constraints on the technology. On the other hand, studying these decoherence processes on small-scale networks made of a few elementary gates could help us in understanding the role of these relaxation mechanisms.

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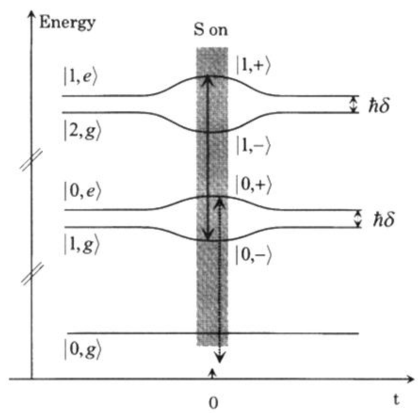

FIG. 3. Position of the atom-cavity energy levels ("dressed levels") as a function of time. The atom is on cavity axis at $t=0$. The classical source S is switched on during a small time interval around $t=0$. It is resonant with the transition between the dressed states $|0,-\rangle$ (originating from $|1,g\rangle$) and $|1,+\rangle$ (originating from $|1,e\rangle$) (solid arrow). It is therefore out of resonance on the transition between the state $|0,g\rangle$ (not affected by the atom-field coupling) and $|0,+\rangle$ (dashed arrow).