Coherence-Preserving Trap Architecture for Long-Term Control of Giant Ryberg Atoms

P. Hyafil,[1] J. Mozley,[1] A. Perrin,[1] J. Tailleur,[1] G. Nogues,[1] M. Brune,[1] J. M. Raimond,[1] and S. Haroche[1,2]

[1]*Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France*

[2]*Collège de France, 11 place Marcelin Berthelot, F-75231 Paris Cedex 05, France*

(Received 6 May 2004; published 3 September 2004)

We present a way to trap a single Rydberg atom, make it long-lived, and preserve an internal coherence over time scales reaching into the minute range. We propose to trap using carefully designed electric fields, to inhibit the spontaneous emission in a nonresonant conducting structure, and to maintain the internal coherence through a tailoring of the atomic energies using an external microwave field. We thoroughly identify and account for many causes of imperfection in order to verify at each step the realism of our proposal.

DOI: 10.1103/PhysRevLett.93.103001 PACS numbers: 32.80.–t, 03.65.–w, 32.60.+i, 42.50.Pq

Giant circular Rydberg atoms are blessed with remarkable properties [1]. They have a long lifetime and a huge electric dipole. Their consequent strong coupling to static or resonant electric fields makes them highly sensitive probes of their environment. In recent years, they have been used, coupled to millimeter-wave superconducting cavities, to test fundamental quantum concepts [2] and to realize elementary quantum logic operations [3,4]. In this context, Rydberg atoms are competing with other systems, such as ions [5] or neutral atoms [6], used or proposed, under various conditions, as tools for the testing of quantum information procedures. A new trend in this field proposes the integration of atomic and mesoscopic systems allowing for new applications of quantum mechanics [7,8]. In this regard, Rydberg atoms are very promising candidates, provided their large sensitivity to electric perturbations can be combated. They have the particular advantage of interacting strongly with microwave fields which can be generated by high frequency electronic circuits.

In this Letter, we describe a general procedure making it possible to trap and manipulate single Rydberg atoms. A circular Rydberg atom-chip trap design stores individual atoms, prepared on demand. This cryogenic electric trap, preventing spontaneous emission, makes circular states stable for minutes. Moreover, it allows for the preparation, preservation, and probing of a millimeter-wave coherence between two levels. More complex architectures of traps, guides, cavities, and detectors could be implemented on a single chip. This paves the way to very high resolution atom-surface and atom-atom interaction studies, to the coherent coupling of giant Rydberg atoms with superconducting mesoscopic circuits, to complex quantum entanglement knitting, and to scalable quantum information operations.

We discuss, for the sake of definiteness, the trap in the specific case of two circular levels e and g with principal quantum numbers $n = 51$ and 50, respectively. These levels have maximum orbital (l) and magnetic (m) quantum numbers ($l = |m| = n - 1$). The e/g transition is at 51.099 GHz. Both circular levels have a long radiative lifetime $T_{sp} = \Gamma_{sp}^{-1} \equiv 30$ ms. Their preservation requires a static electric (or magnetic) field. This defines a physical quantization axis (unit vector $\boldsymbol{u}$) and prevents mixing with other states in the hydrogenic manifold.

The radiative lifetime, although long, can be greatly increased by inhibiting spontaneous emission (SE) [9]. Both levels e and g have a single decay channel, the emission of a millimeter-wave photon circularly polarized in a plane perpendicular to $\boldsymbol{u}$ ("$\sigma^{\pm}$ polarization"). This emission is blocked when the atom is placed between two parallel conducting planes (normal to Oz, itself ideally parallel to $\boldsymbol{u}$) separated by a distance $d < \lambda/2$ ($\lambda \sim 6$ mm being the emitted photon wavelength). Lifetime increases by a factor of a few tens have been demonstrated in the millimeter-wave domain [10]. Levels e and g can simultaneously be made long-lived. There are two main contributions to the residual spontaneous emission rate Γ. The first, $\Gamma_a = \Gamma_{sp}\sin^2\theta$, is due to any eventual angle θ between Oz and $\boldsymbol{u}$. The second, Γ_s, is due to imperfections in the conducting surfaces. Both these rates are enhanced by thermal processes, and it is thus essential to operate at cryogenic temperatures, below 1 K. It is important to note that, even in this SE-inhibiting structure, the e/g transition can be probed by means of an evanescent field produced by an intense source. Note also that the atom-surface distance (0.5 mm in the trap considered here) is large enough that van der Waals interactions are but a small perturbation.

Taking advantage of this extended lifetime requires a trapping mechanism compatible with SE inhibition. We propose here an electric trap relying on the quadratic Stark polarizability of e and g [$\alpha \equiv -0.2$ kHz/(V/m)^2 for weak fields] in a field $\boldsymbol{E}$ approximately aligned with Oz (unit vector $\boldsymbol{u}_z$). Since circular states are high-field seekers, there can be no static field trap. We therefore turn to a dynamic scheme, reminiscent of the Paul trap [5], combining static and oscillating fields. Our design is

comparable to that discussed in Ref. [11] for ground-state atoms. Our trap geometry is presented in Fig. 1(a). The SE-inhibiting planes are now made up of concentric electrodes. The static potential U_0 creates a homogeneous directing field $E_0\boldsymbol{u}_z$. The potential U_1, oscillating at ω_1, creates a smaller, ac, approximately hexapolar field $\boldsymbol{E}_1$ [see Fig. 1(b)]. The atomic Stark energy, $-\alpha(E_0\boldsymbol{u}_z + \boldsymbol{E}_1)^2$, has a roughly quadratic spatial dependence. In order to cancel $\boldsymbol{E}_1$ at the origin O for all times, we apply the potential $\pm\eta U_1$ to the outer electrodes, the factor η being determined by the electrode geometry. Finally, the yet smaller static potential U_2 creates an approximately quadrupolar field. This provides a force, nearly constant in the trap region, compensating gravity (antiparallel to Oz).

The trap performance is assessed through numerical calculations. In order to account for edge effects, we compute the electric field using SIMION software. The corresponding atomic energies are derived from the hydrogenic Stark formulas up to second order. The atomic trajectories are computed using an adaptive-step Runge-Kutta method. We set initial conditions corresponding to an atomic cloud in a magnetic microtrap with an adjustable temperature T_0. For $U_0 = 0.2$ V, $U_2 = -0.003$ V and an hexapolar potential $U_1 = 0.155$ V oscillating at $\omega_1 = 2\pi \times 430$ Hz, the resulting motion is the combination of a fast micromotion, at frequency $\omega_1/2\pi$, with a slow oscillation whose longitudinal (along Oz) and transverse (orthogonal to Oz) frequencies are 175 and 64 Hz, respectively. For such low frequencies, the orientation of the circular orbit adiabatically follows the space- and time-dependent direction $\boldsymbol{u}$ of the local electric field [12]. At $T_0 = 90$ μK, the motion has an extension of around 100 μm. We have checked that for $T_0 > 100$ nK, the atomic excursion in the Rydberg trap is much larger than the de Broglie wavelength, allowing a classical treatment. The trap depth, T_d, which we define as the T_0 value for which half of the atoms remain within 400 μm of the origin, is $T_d = 180$ μK, well within the reach of standard laser cooling techniques. We here use potentials in the volt range (much lower than in [11]), compatible with the

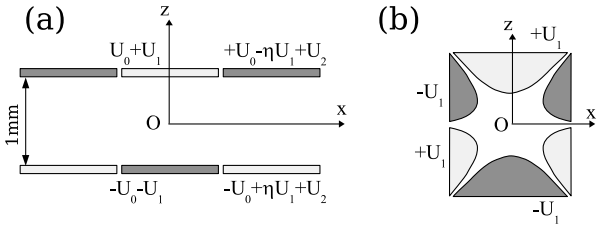

FIG. 1. (a) Section of the trap in a vertical xOz plane, with applied potentials. The trap has a cylindrical symmetry around Oz. The diameter of the inner electrode is 1 mm. The plate spacing, 1 mm, is appropriate for spontaneous emission inhibition. The electrodes are shaded according to the phase of the oscillating potential U_1. (b) Electrode geometry creating an exact hexapolar potential. The analogy with the geometry of (a) is conspicuous.

coherence-preservation scheme detailed below. Deeper traps are achievable with higher voltages. The electrode planes efficiently inhibit SE in the trap since the mean angle θ between $\boldsymbol{u}$ and Oz is only 10 mrad for atoms at 90 μK, corresponding to a residual lifetime of $1/\Gamma_a = 300$ s.

Deterministic loading of the trap with a single Rydberg atom can be realized by the "dipole blockade" effect [13]. This ensures the preparation of one and only one low-angular momentum Rydberg state by laser excitation [14]. The level shifts due to the dipole-dipole interaction (1 GHz for two $n = 50$ atoms separated by 1 μm) make the laser nonresonant for a second Rydberg excitation. A correctly designed laser excitation chain could perform a "π-pulse," whose duration could be as short as a few μs, preparing exactly one Rydberg atom with a probability close to 1 [14]. This single atom can then be transferred, within 20 μs, into the circular state by an adiabatic process [3]. The short duration of this sequence allows for recapture in the electric trap before significant drifting has occurred. To create the initial high density atomic cloud, we plan to work with ground-state atoms magnetically confined on an atom chip [15], which can provide submicron-sized samples at temperatures T_0 as low as a few hundred nK [16]. A double layer configuration would allow superposition of the magnetic and the electrodynamic traps, with gold electrodes on top of the current-carrying superconducting wires necessary for the magnetic trap. The gold layer will efficiently inhibit spontaneous emission, while not significantly perturbing the trapping magnetic field created by the wires of the lower layer. This field is switched off upon Rydberg state excitation.

The Stark polarizabilities of levels e and g being slightly different, the e/g transition is dramatically broadened in the electric field trap. An atom, prepared from a cloud at 0.3 μK, experiences a mean electric field amplitude, $E_a = 400$ V/m, with typical variations of ± 1 V/m over its trajectory. Figure 2(a) shows the energy levels as a function of the electric field amplitude. Atomic motion results in a 20 kHz broadening of the transition. An e/g coherence therefore decays within a few tens of μs. In addition, the trajectories for e and g are rapidly separated ("Stern-Gerlach" effect due to the different trap potentials experienced by e and g). Coherence is lost when this separation exceeds the wave-packet coherence length, of the order of the de Broglie wavelength (here, about 0.8 μm).

Similar broadenings are observed in optical dipole traps for ground-state atoms, where the potential energy is also, in general, level dependent. In this case, well-chosen trapping laser wavelengths minimize the effect [17]. In the circular atom trap, we propose to use instead a microwave state dressing. The atom is illuminated with a microwave field at angular frequency ω_0 polarized parallel to Oz, detuned by $\delta_0 = \omega_{gi}(E_a) - \omega_0 > 0$ to the

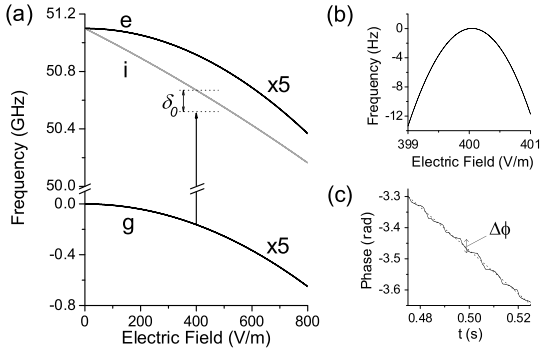

FIG. 2. (a) Stark energy of levels e, g, and i versus electric field. States g and e have a small, approximately quadratic Stark effect, magnified by a factor of 5 for the sake of clarity. Level i has a much larger, linear Stark effect. The microwave dressing (vertical arrow) predominantly mixes g and i and reduces the difference in Stark polarizability between e and g. (b) Relative frequency $\omega_{eg}(E) - \omega_{eg}(E_a)$ around the average trap field E_a in the presence of the microwave dressing. (c) Solid line: phase accumulated by an e/g coherence over a 40 ms period in the presence of the microwave dressing showing a step structure (average step size $\Delta\phi$) in phase with the atomic motion. Dashed line: a linear fit (slope 6.9 rad/s) over the total time period of 1 s highlighting the approximately linear evolution.

red of the i/g transition Stark shifted by the average field E_a [see Fig. 2(a)]. This microwave field is therefore π polarized and compatible with the boundary conditions set by the trap electrodes. It is assumed to be a propagating guided wave. Its amplitude, independent of z and x, is maximal at the origin (corresponding Rabi frequency Ω_0) and varies sinusoidally with y, having nodes at $y = \pm 1$ cm. To first approximation, this field couples g to the Rydberg state i ($n = 51$, $m = m_g = 49$), which experiences a large linear Stark effect [polarizability 1 MHz/(V/m)]. The Stark polarizability of the "dressed" g level is thus significantly modified. The dressing field has a smaller effect on e since the π-polarized transition from e up to the $n = 52$ manifold is far off resonance. The Rabi frequency Ω_0 and the detuning δ_0 of the dressing microwave can therefore be tailored to cancel the first and to minimize the second order terms in the expansion of $\omega_{eg}(E)$ around E_a. Note that the dressed g level can still decay only through the emission of a σ-polarized microwave photon. The exact shift of levels g and e for an atom located at $\boldsymbol{r}$ is calculated by an explicit diagonalization of the atom-field Hamiltonian, involving eight hydrogenic manifolds, taking into account the local dressing amplitude, time-dependent electric field, and angle θ between Oz and $\boldsymbol{E}(\boldsymbol{r}, t)$. Note that a nonzero θ value causes the atom to experience a reduced component of the dressing microwave parallel to $\boldsymbol{E}(\boldsymbol{r}, t)$, and hence $\boldsymbol{u}$, and, accordingly, a small microwave field orthogonal to $\boldsymbol{u}$. We have checked that the latter plays no important role, being far off resonance from any allowed transition originating from g or e.

The optimal parameters Ω_0 and δ_0 have reasonable values: $2\pi \times 200.000$ MHz and $2\pi \times 556.230$ MHz, respectively. The dressed transition frequency, shown in Fig. 2(b), varies by only $\sim$10 Hz over the ± 1 V/m electric field range explored by an atom for $T_0 = 0.3$ μK. The dressing reduces the transition broadening by over 3 orders of magnitude. A quantitative confirmation of this insight must take into account the modulation of the atom-dressing field coupling due to the time-varying angle θ contributing to a residual broadening of the line (of about 0.5 Hz in our case). Note that the adverse influence of stray electric fields (for instance, those due to patch effect) will also be dramatically reduced. Based on the results of Ref. [18], we estimate a patch-induced field to have an average amplitude of 8 mV/m with a dispersion of 0.4 mV/m over the trap volume.

In order to estimate the coherence decay time T_2 we simulate a Ramsey interferometry experiment. The atom undergoes two short microwave $\pi/2$ pulses, resonant on the e/g transition and separated by a long delay t. We compute many trajectories originating from an atomic cloud of size 0.3 μm, centered at O, at temperature $T_0 = 0.3$ μK and receiving a single optical recoil along Ox during Rydberg excitation. The phase $\phi(t)$ accumulated by an e/g coherence is integrated over each trajectory. Figure 2(c) represents this phase evolution for a given trajectory over a 40 ms time interval. Most of the dephasing occurs at the turning points of the atomic macromotion, where θ and $E - E_a$ are maximum. At these points the influence of the micromotion, being at a higher frequency and of smaller amplitude, averages, resulting in an accumulated dephasing $\Delta\phi$, almost identical from one turning point to another. Therefore, over times long compared to the trap period, the resulting dephasing evolves linearly. The final fringe contrast is $C(t) = [\overline{\cos\phi(t)}^2 + \overline{\sin\phi(t)}^2]^{1/2}$ (where the bar denotes an average over all trajectories). The time evolution of C, shown in Fig. 3, provides an estimate of T_2 around 25 ms.

As noted earlier, the phase drift is almost perfectly linear with time for all trapped trajectories. The phase spreading can therefore be combated using an echo technique reminiscent of photon echoes and of NMR refocusing schemes. Coherence-preserving echoes have also been tested for trapped ground-state atoms or ions [19]. At a time $t_\pi = 0.5$ s after the first Ramsey pulse, we "apply" a π pulse on the e/g transition, exchanging the populations of the two states and hence changing the sign of the accumulated phase (we mimic pulse imperfections by a 10% Gaussian dispersion of the rotation angle). During the subsequent evolution, the phase drift continues as before. The phase of each trajectory thus returns towards zero. At time $t = 2t_\pi = 1$ s, all phases are zero within an uncertainty of the order of the average phase step amplitude $\Delta\phi$. Figure 3 also presents the contrast C obtained

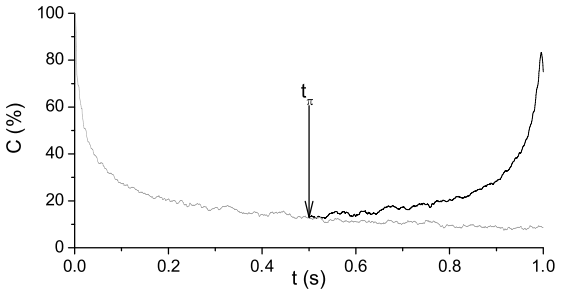

FIG. 3. Simulated Ramsey fringe contrast C as a function of the time interval t between two $\pi/2$ pulses. Grey line: contrast decay without echo, averaged over 10 000 trajectories. The contrast undergoes a nonexponential decay, falling to 50% in 24 ms, and to 13% in 0.5 s. Black line: C versus t for the same trajectories with a π pulse at $t_\pi = 0.5$ s. The sharp contrast revival at $t = 1$ s peaks at 82%.

under these conditions as a function of t. It increases sharply up to 82% around $t = 2t_\pi = 1$ s. This very high contrast corresponds to an effective $T_2 = 5.0$ s. Even for atoms at $T_0 = 1$ μK, we obtain $C(2t_\pi) = 57.3\%$. More complex echo sequences can be envisaged to improve the final Ramsey fringe contrast. Ideal π pulses repeated at shorter time intervals can maintain the coherence over time scales in the minute range.

We have shown that the combination of SE inhibition, Stark trapping, microwave-dressing, and echo techniques makes it possible to manipulate Rydberg atoms coherently over long time intervals. The Stark trap presents advantages as compared to magnetic traps, which do not possess an equivalent coherence-preservation scheme to combat the dephasing due to the differential Zeeman effect of e and g. Traps based on ponderomotive forces [20], requiring large laser powers, are hardly compatible with a cryogenic environment.

We have also designed electric traps with smaller electrodes and checked that they are compatible with the coherence-preservation scheme. These would bring the trapped atom much closer to the electrode surface which can be of interest for atom-surface studies. Elaborating on our scheme, one can design a variety of different structures such as waveguides or "conveyor belts." These would operate via the use of electrode arrays, easily produced by lithographic techniques, and a proper commutation of the voltages applied to them. Field-ionization Rydberg atom detectors could also be realized "on chip," using the accelerated electron to trigger a superconducting to normal transition in a mesoscopic wire [21]. These "everlasting" giant Rydberg atoms open a wealth of fascinating perspectives for fundamental studies. High spectroscopic resolution, at the Hertz level, makes it possible to study atom-surface interactions of the Casimir type, at millimeter-range distances [9,22]. Atom-atom [23] interaction at long range, possibly mediated by a superconducting line [7], could also be investigated. The coherent interaction of atoms with superconducting quantum circuits on the chip surface is also a promising avenue of inquiry. Cavity QED experiments could be realized with high-Q planar transmission-line cavities [8]. Atom-atom entanglement could be generated through cavity-assisted collisions [4], the scheme being, in principle, extendable to much more complex architectures for quantum information processing.

Laboratoire Kastler Brossel is a laboratory of Université Pierre et Marie Curie and ENS, associated to CNRS (UMR 8552). We acknowledge support of the European Community (QUEST and QGates projects) and of the Japan Science and Technology Corporation (International Cooperative Research Project: Quantum Entanglement).

[1] T. F. Gallagher, *Rydberg Atoms* (Cambridge University Press, Cambridge, 1994).
[2] G. Nogues *et al.*, Nature (London) **400**, 239 (1999); P. Bertet *et al.*, Nature (London) **411**, 166 (2001).
[3] J.-M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73**, 565 (2001).
[4] S. Osnaghi *et al.*, Phys. Rev. Lett. **87**, 037902 (2001).
[5] D. Leibfried *et al.*, Rev. Mod. Phys. **75**, 281 (2003).
[6] O. Mandel *et al.*, Nature (London) **425**, 937 (2003).
[7] A. S. Sorensen *et al.*, Phys. Rev. Lett. **92**, 063601 (2004).
[8] A. Blais *et al.*, Phys. Rev. A **69**, 062320 (2004).
[9] S. Haroche, in *Fundamental Systems in Quantum Optics, Les Houches Summer School, Session LIII*, edited by J. Dalibard, J.-M. Raimond, and J. Zinn-Justin (North-Holland, Amsterdam, 1992), p. 767.
[10] R. G. Hulet, E. S. Hilfer, and D. Kleppner, Phys. Rev. Lett. **55**, 2137 (1985); S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999).
[11] E. Peik, Eur. Phys. J. D **6**, 179 (1999).
[12] M. Gross and J. Liang, Phys. Rev. Lett. **57**, 3160 (1986).
[13] M. D. Lukin *et al.*, Phys. Rev. Lett. **87**, 037901 (2001).
[14] M. Saffman and T. G. Walker, Phys. Rev. A **66**, 065403 (2002).
[15] J. Reichel, W. Hänsel, and T. W. Hänsch, Phys. Rev. Lett. **83**, 3398 (1999).
[16] W. Hänsel *et al.*, Nature (London) **413**, 498 (2001).
[17] H. Katori *et al.*, Phys. Rev. Lett. **91**, 173005 (2003).
[18] V. Sandoghdar *et al.*, Phys. Rev. A **53**, 1919 (1996).
[19] M. F. Andersen, A. Kaplan, and N. Davidson, Phys. Rev. Lett. **90**, 023001 (2003); S. Kuhr *et al.*, Phys. Rev. Lett. **91**, 213002 (2003); M. Rowe *et al.*, Quantum Inf. Comput. **2**, 257 (2002).
[20] S. K. Dutta *et al.*, Phys. Rev. Lett. **85**, 5551 (2000).
[21] A. D. Semenov, G. N. Gol'tsman, and R. Sobolewski, Supercond. Sci. Technol. **15**, R1 (2002); P. K. Day *et al.*, Nature (London) **425**, 817 (2003).
[22] M. Marrocco *et al.*, Phys. Rev. Lett. **81**, 5784 (1998); F. Shimizu, Phys. Rev. Lett. **86**, 987 (2000); M. Boustimi *et al.*, Phys. Rev. Lett. **86**, 2766 (2001).
[23] D. Jaksch *et al.*, Phys. Rev. Lett. **85**, 2208 (2000).