Single Atom as a Mirror of an Optical Cavity

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By tightly focusing a laser field onto a single cold ion trapped in front of a far-distant dielectric mirror, we could observe a quantum electrodynamic effect whereby the ion behaves as the optical mirror of a Fabry-Pérot cavity. We show that the amplitude of the laser field is significantly altered due to a modification of the electromagnetic mode structure around the atom in a novel regime in which the laser intensity is already changed by the atom alone. We propose a direct application of this system as a quantum memory for single photons.

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Atom-photon interactions are essential in our understanding of quantum mechanics. Besides the two processes of absorption and emission of photons, coupling of radiation to atoms raises a number of questions that are worth investigating for a deeper theoretical and thus interpretational insight. The modification of the vacuum by boundaries is among the most fundamental problems in quantum mechanics and is widely investigated experimentally. In quantum optics, most studies make use of optical cavities that modify the vacuum-mode density of the field around atoms to change their emission properties [1–4]. Another more recent research area investigates the direct coupling of tightly focused light to atoms in free space, using high numerical aperture (NA) elements [5–11]. There, precise control over the motion of the individual atoms is crucial to reach the regime of strong atom-light interactions [12]. Recent research in this direction has been performed using cold neutral rubidium atoms [13], single cold molecules [14], quantum dots [9], superconducting circuits [11], as well as single trapped ions [15,16]. The strong confinement offered by Paul traps, the readily available sideband-cooling techniques, and the ability to perform efficient and deterministic quantum gates [17] make single ions good candidates for such free-space quantum communications [18].

In this Letter, we present a first step towards merging the field of cavity QED with free-space coupling, using an ion trap apparatus. We set up a novel atom-mirror system in which a weak probe field is tightly focused onto a single trapped ion at the focus of a lens-mirror system. The atomic coupling to the probe is thereby modified by a single mirror in a regime where the probe intensity is already significantly altered by the atom without the mirror. Furthermore, we show that in the limit of a high numerical-aperture lens the mirror-induced change in the vacuum-mode density around the single atom can in principle modulate the atom's coupling to the probe, the total spontaneous decay, and the Lamb shift, so that the atom behaves as the mirror of a high-finesse cavity. A measurement of the latter two quantities was in fact performed in [19,20] by monitoring the excited state population through fluorescence detection. Absorption spectroscopy here enables us to measure the first-order coherence between the driving laser and the backscattered light and thus to estimate the amplitude of the coherently backscattered field. Finally, we show that our setup allows almost full suppression and enhancement by a factor of 2 of the atomic coupling constant in the probe mode.

We first consider the single atom as an optical reflector, as depicted in the setup of Fig. 1(a). Figures 1(b)–1(d) show the positioning, central frequency, and transmission bandwidth of the single atom-mirror setup, respectively. We use a single $^{138}Ba^{+}$ ion in a ring Paul trap [21]. As shown in Fig. 1(c), a narrow band laser field at 493 nm

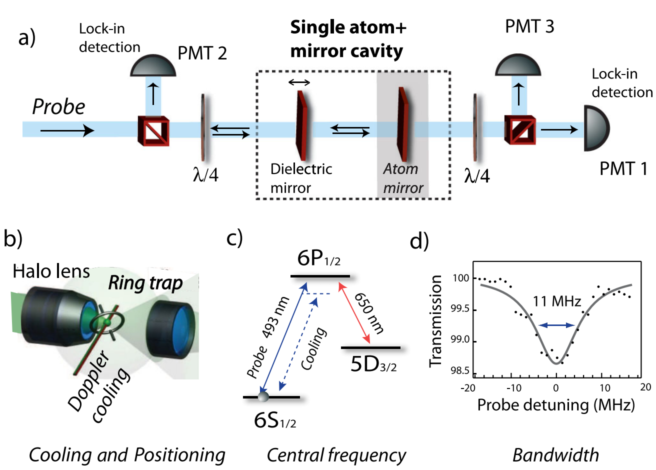

FIG. 1 (color online). (a) Single ion + mirror setup. The probe field is coupled to the atom-mirror cavity through the dielectric mirror that is mounted on piezoelectric stages. The intensity of the probe is measured in transmission by PMT1 and in reflection by PMT2. PMT3 is used for measuring the ion fluorescence. The main properties of the single atom operated as a mirror are shown in (b) positioning, (c) central frequency, and (d) transmission, as measured without the dielectric mirror.

provides Doppler cooling 50 MHz red detuned from the $S_{1/2}$-$P_{1/2}$ transition, while a laser at 650 nm recycles the atomic population from the $D_{3/2}$ manifold. The cooling beam intensity is set far below saturation yet allowing cooling to the Lamb-Dicke regime with a typical final population of about $\langle n\rangle \approx 13$.

For extinction of a laser field by the ion in free space, we use a very weak probe beam resonant with the $S_{1/2}(m_F = +1/2)$-$P_{1/2}(m_F = -1/2)$ transition. As shown in Fig. 1(b), the probe beam is overlapped with part of the dipole emission pattern of the ion using a custom-designed objective with a numerical aperture of 0.4. A 1.5% fraction of the ion's 493 nm fluorescence together with the transmitted part of the probe beam is then collected by a microscope objective and detected by the photomultipliers PMT3 and PMT1, respectively. Intensity modulation of the 650 nm laser beam, as described in [21], enables us to efficiently discriminate the fluorescence from the extinction signal. Figure 1(d) shows the typical Lorentzian dependence of the transmission profile, measured without the dielectric mirror. It shows a width of 11 MHz and a maximal extinction of 1.35%.

In the case of coherent reflection of a laser field by a single atom, the backscattered field must interfere with the driving laser. To verify this, we construct the system shown in Fig. 1(a) by inserting a dielectric mirror 30 cm away from the atom into the probe path, with a reflectivity $|r|^2 = 1 - |t|^2 = 99.7\%$. We align it so that the ion is reimaged onto itself and shine the resonant probe through it. Using the Fabry-Pérot cavity transmissivity, and modeling the atom as a mirror with amplitude reflectivity 2ϵ [22], one can naively assume that the intensity transmissivity of the probe reads

$$T = \left| \frac{t(1-2\epsilon)}{1-2r\epsilon e^{i\phi_L}} \right|^2, \quad (1)$$

where $\phi_L = 2k_L R$, R is the atom-mirror distance, and k_L the input probe wave vector. The finesse $\mathcal{F} = \pi 2\epsilon r/[1-(2\epsilon r)^2]$ of such a cavitylike setup can in fact be made very large by using a high numerical-aperture lens such that $\epsilon \rightarrow 50\%$ together with a highly reflective dielectric mirror. In our experiment, the atom reflectivity is less then 1% [21], so the transmitted intensity is well approximated by

$$T \approx |t|^2 |1 - 2\epsilon + 2\epsilon r e^{i\phi_L}|^2. \quad (2)$$

By tuning the distance between the dielectric mirror and the ion, one would therefore expect a dependence of the transmitted signal on the cavity length, provided that the temporal coherence of the incoming field is preserved upon single-atom reflection.

The operation of our ion-mirror system is shown in Fig. 2(a). As the mirror position is scanned, we indeed observed clear sinusoidal oscillations of the power detected in PMT1 on a wavelength scale. These results reveal that the elastic backscattered field is interfering with the transmitted probe, and that the ion is very well within the Lamb-Dicke regime. Figure 2(b) shows the fluorescence rate measured at PMT3 for the same experimental conditions but with the probe field blocked. The intensity change of the fluorescence rate is the result of the self-interference of single photons, which can be expressed as $I = I_0[1 + V\cos(\phi_L)]$ [19,23]. With our ion-mirror distance (30 cm), the interference contrast V is mostly limited by residual aberrations of the imaging optics and atomic motion [19]. As predicted by the formula for the transmission T [Eq. (2)], the two signals in Figs. 2(a) and 2(b) oscillate perfectly in phase. The oscillations are, however, observed with a lower contrast than for the extinction coefficient (defined as $E = 1 - T/|t|^2$, and plotted on the right axis). As we will show, this pronounced difference stems from an aberration-free dependence of the extinction contrast. We then perform another experiment in which we replace the high reflectivity mirror by a 25%/75% mirror. The results are shown in Figs. 3(a) and 3(b) where we simultaneously recorded the reflected and transmitted powers measured on PMT2 and PMT1, respectively.

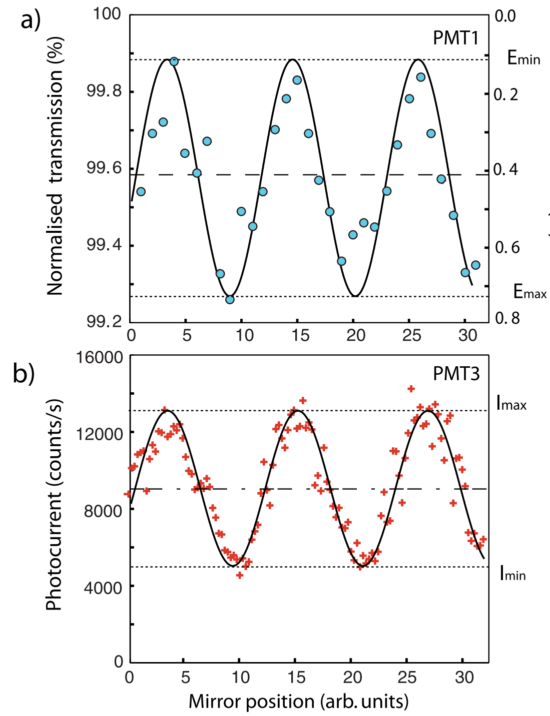

FIG. 2 (color online). (a) Normalized transmission $T/|t|^2$ of the probe through the single-atom-mirror system as a function of the mirror position, with a 99.7% reflective dielectric mirror. The dashed lines shows the transmission of the probe when the mirror is slightly misaligned. The dotted lines show the minimum and maximum extinction values used for estimating the contrast V'. (b) The single photon interference fringe measured on PMT3. Solid lines are the sinusoidal fits to the data. The dotted lines show the minimum and maximum photocurrent values used for estimating the contrast V. Error bars are on the order of 0.05% for all the points.

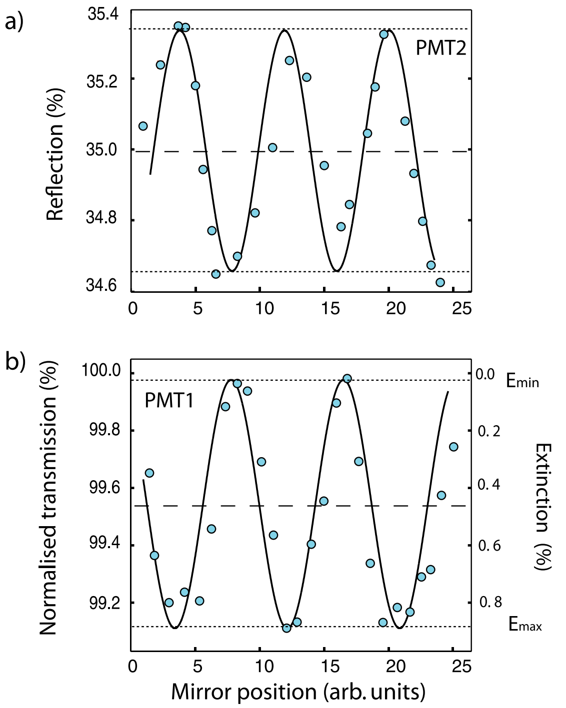

FIG. 3 (color online). (a) Intensity of the probe reflected off the cavity, normalized to the probe intensity without ion, and using a 75% reflective dielectric mirror. (b) The transmission of the probe through the atom-mirror system as a function of the mirror position, normalized to the mirror transmissivity. The dashed line in (a) shows the reflection of the probe without the ion and in (b) the transmission with the mirror misaligned from the ion.

With this mirror reflectivity, we are able to measure the change of the probe power being reflected off the cavity, which we found to be exactly out of phase with the transmitted signal, as is predicted for a Fabry-Pérot cavity response. We note that, here again, an unexpectedly large extinction contrast is observed.

The contrast $V' = (E_{\rm max} - E_{\rm min})/(E_{\rm max} + E_{\rm min})$ of the ion + mirror cavity extinction plotted in Figs. 2(a) and 3(b) and the ion's single photon interference contrast in Fig. 2(b) clearly differ. To understand this effect, we will consider the influence of aberrations by including a phase shift to each of the contributing amplitudes of the transmitted field at various points on the lens. As shown in the Supplemental Material [24], the transmissivity of the probe, in the limit of a high dielectric mirror reflectivity, is then

$$T \approx |t|^2\{1 - 4\bar{\epsilon}(1 - \cos(\phi_L)\}. \quad (3)$$

Here $\bar{\epsilon} = \epsilon' J_0(\eta)$, $J_0(\eta)$ is the first-order Bessel function of the first kind, and $\eta = 2\pi\sigma_{\rm ab}/\lambda$ where $\sigma_{\rm ab}$ is the root mean square amplitude of the aberrations and λ is the optical wavelength. We then obtain the normalized extinction plotted Fig. 2(a) to be

$$E = 4\bar{\epsilon}[1 - \cos(\phi_L)]. \quad (4)$$

The contrast of E is then free of the aberrations that one could expect to play a role. However, when making the same substitutions in the formula for the single photon interference that we observed in Fig. 2(b), one gets the intensity

$$I = I_0[1 + J_0(\eta)\cos(\phi_L)], \quad (5)$$

which shows a direct dependence on the aberrations. The two intensities that contribute to the extinction E in fact arise from an interference between the input and the scattered amplitudes that carry the same global phase shifts. This explains the larger contrast measured in Figs. 2(a) and 3(b) over Fig. 2(b). This observation will be important for precise characterization and control of the tight focusing of optical fields onto single trapped particles.

We now investigate whether the naive Fabry-Pérot interpretation that we used to describe our results is valid. One could indeed wonder how the modification of the quantum vacuum around the atom affects our results. It is clear that the dielectric mirror imposes new boundary conditions that will change the vacuum-mode density close to the atom, but it is less obvious how much it will contribute to the probe intensity changes that we observe in this experiment. One can in fact show (see Supplemental Material [24]) that solving the multimode Heisenberg equations in a time-dependent perturbation theory gives

$$T = |t|^2 \left| 1 - \frac{2g_\epsilon \bar{g}^*}{\tilde{\gamma} + i\tilde{\Delta}} \right|^2, \quad (6)$$

assuming the input probe to be resonant with the atomic transition. Here, g_ϵ denote the atomic coupling strength in the probe mode, $\bar{g}$ is the mean coupling to all the modes, and $\tilde{\gamma}$ and $\tilde{\Delta}$ are the decay and level shifts modified by the presence of the mirror. Their expressions can be evaluated using the appropriate spatial mode function for this system [25], and we can then show that

$$\frac{g_\epsilon \bar{g}^*}{\tilde{\gamma} + i\tilde{\Delta}} = \frac{\epsilon(1 - re^{i\phi_L})}{1 - 2r\epsilon e^{i\phi_L}}. \quad (7)$$

After combining this relation with Eq. (6) we obtain the same transmissivity as was obtained by modeling the atom as a mirror with reflectivity 2ϵ [Eq. (1)]. Interestingly, the QED calculations yield the same mathematical results as the direct Fabry-Pérot calculation.

In this QED approach, it was not necessary to invoke multiple reflections off the atom for the Fabry-Pérot-like transmission to appear. The transmission of the probe through the single atom + mirror system is mathematically equivalent to a cavity, but the origin of the peaked transmission profile can be interpreted as a line-narrowing effect due to the QED-induced changes of the spontaneous emission rate and level shift. In our experiment, we observed a change of the coupling between the atom and the probe mode, due to the modification of the mode density induced by the mirror. Deviations from the sinusoidal shape due to line narrowing would be visible for a lens covering a solid angle of more than 10%. We note that, with this interpretation, the aberration-free dependence of the extinction contrast is analogous to an almost complete cancellation and enhancement by a factor of 2 of the atomic coupling constant in the probe mode.

We foresee a direct application of our system. In discrete variable quantum communications, and specifically for quantum repeater architectures, single photons must be stored and released from stationary qubits [26,27] to prevent the unavoidable losses in optical fibers [28]. The required efficient coupling between a single photon and a single atom can be obtained through the use of a high-finesse cavity [26,29] or parabolic mirrors for mode matching the incoming field with the whole atomic dipole field [30]. Our single atom-mirror setup is an attractive alternative solution for full absorption of a single photon. In such a scenario, the retroreflection of the backscattered field by the mirror mediates the required interference effect so that the excitation probability of the atom can reach more than 50% [15,31]. However, unlike standard lossless mirrors, the ion will fully reflect the light back into the probe mode only for $\epsilon = 50\%$ so, in the realistic NA case, the scattered field is emitted into almost 4π sr. With standard mirrors, impedance matching can be reached by matching the mirror reflectivities. Since impedance matching here is not immediately fulfilled, in order to attain a steady state transmission of the optical field through such a system, one can optically pump a fraction of atomic population to another state to match the input mirror reflectivity. Implementing a dynamic coherent transfer of population [27,32] to another metastable ground state will furthermore allow efficient and long-lived quantum storage of a single photon pulse in the atom. Alternatively, one could ramp the mirror position from the antinode to the node of the standing wave so as to match the incoming photon's temporal profile to the ion-mirror system and store the photon in the long-lived atomic excited state [25]. Although the present results are obtained in the elastic scattering regime with two levels, our experimental results may be seen as the first tests of such a new single atom-photon interface.

In conclusion, we successfully observed the operation of a single atom as an optical mirror of a Fabry-Pérot-like cavity. Our investigations are performed in a novel regime where a significant fraction of the power of a probe field can be affected by the atom in free space. This allows us to realize an experiment in which both the properties of an atom as a reflector and the modification of the atomic coupling constant can play a role. Although a simple cavity interpretation lends itself naturally to a description of our experiment, a more general QED formulation should be preferred for an unambiguous discrimination of the involved mechanisms. Interestingly, for our experimental parameters (weak resonant excitation, small atom-mirror distances), we found that both interpretations are equivalent. Besides the appealing quantum memory application that we presented above, our setup has a number of other realistic prospects. It will, for instance, be a useful tool for operating the ion as an optical switch, similar to the single atom transistors using electromagnetically induced transparency implemented in [11,21,33,34] or using a population inversion [10].

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