

## Electromagnetically Induced Transparency from a Single Atom in Free Space

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In this Letter, we report an absorption spectroscopy experiment and the observation of electromagnetically induced transparency from a single trapped atom. We focus a weak and narrow band Gaussian light beam onto an optically cooled  $^{138}\text{Ba}^+$  ion using a high numerical aperture lens. Extinction of this beam is observed with measured values of up to 1.35%. We demonstrate electromagnetically induced transparency of the ion by tuning a strong control beam over a two-photon resonance in a three-level  $\Lambda$ -type system. The probe beam extinction is inhibited by more than 75% due to population trapping.

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Atom-photon interfaces will be essential building blocks in future quantum networks [1,2]. Here, photons are usually adopted as messengers due to their robustness in preserving quantum information during propagation, while atoms are suited to store the information in stationary nodes. The efficient transfer of quantum information between atoms and photons is then essential and requires controlled photon absorption and emission with a very high probability. The requisite strong coupling can be achieved, for example, using high finesse cavities [3–5] or large atomic ensembles [6,7], which are the most studied routes towards such goals.

Coupling of radiation to a single atom in free space is generally considered to be weak; however, technological advances with large aperture lenses [8] and mirrors [9], recently led many groups to reconsider this point of view. Novel experiments demonstrated extinctions of about 10% from single Rubidium atoms [10], single molecules [11,12], and quantum dots [13]. More recently, the phase shift of light induced by a single Rubidium atom [14], and nonlinear switching with a single molecule [15] were observed. These experiments demonstrate first steps towards quantum optical logic gates and quantum memories with single atoms in free space.

Long-term and controlled storage of quantum information will likely require electromagnetically induced transparency (EIT). This technique is widely used to control the absorption of weak light pulses or single photons in atomic ensembles [7,16] and high finesse cavities [17]. Here, a Raman transition in  $\Lambda$ -type three-level atoms is driven by the weak probe light and a strong control laser. Because of an interference effect between the probability amplitudes of the dipoles on the control and probe field transitions, the probe is transmitted within a narrow spectral window. Consequently, the change of the control laser intensity can gate the propagating probe field between absorption and transmission. Furthermore, adiabatic switching of the control laser can trigger storage and retrieval of probe light by the atoms [1,18].

So far, EIT has been a phenomenon specific to optically thick media consisting of ensembles of many atoms [18], where both the optical fields and the atomic states are modified. However, quantum information processing requires single well-defined qubits that can be individually manipulated to perform deterministic quantum gates. It thus appears very appealing to use single atom-single photons interactions to distribute information over the nodes of a quantum network. In single-atom experiments, the related effect of coherent population trapping has been observed on the fluorescence field, which reveals modifications of the atomic population, but leaves the transmitted optical fields without significant change. While EIT with a single atom in a cavity has been demonstrated just recently [19–21], its free-space counterpart still remains to be proven. A system based on this technique could easily be used as a quantum interface [22], an efficient single-atom switch or a programmable phase shifter of a weak coherent beam or a single photon field in a quantum network.

Currently, trapped ions are widely investigated as promising candidates for quantum information processing [23]. The good control over the electronic and motional states of ions in Paul traps makes them ideal systems to investigate the coupling of radiation to single absorbers [24,25]. In this Letter, we investigate a first step towards a free-space quantum interface by demonstrating an extinction of 1.35% and EIT from a single trapped ion. First, we discuss a simple theoretical description of extinction or reflection of a weak probe from a single atom. It uses a perturbative input-output formalism to relate the incoming field,  $\hat{a}_{\text{in}}$ , and the outgoing field,  $\hat{a}_{\text{out}}$ , through their interaction with the atom [26]. In the Markov limit this gives the relation  $\hat{a}_{\text{out}}(t) = \hat{a}_{\text{in}}(t) + i\sqrt{2\gamma_{\text{in}}}\hat{\sigma}(t)$ , where  $\hat{\sigma}(t)$  is the atomic coherence and  $\gamma_{\text{in}}$  is the effective coupling of the input to the atom.  $\gamma_{\text{in}}$  can also be expressed by the total decay rate of the excited state  $\gamma$  and the fraction  $\epsilon$  of the full solid angle covered by the incoming field as  $\gamma_{\text{in}} = \epsilon\gamma$ . Solving the two-level atom Bloch equations in the weak excitation limit, and in steady state, gives  $\hat{\sigma} = i\sqrt{2\gamma_{\text{in}}}\hat{a}_{\text{in}}/(\gamma + i\Delta)$ ,

where  $\Delta$  is the frequency detuning of the probe from the excited state. The transmission of the intensity of a probe field finally reads

$$T = |1 - 2\epsilon\mathcal{L}(\Delta)|^2, \quad (1)$$

where  $\mathcal{L}(\Delta) = \gamma/(\gamma + i\Delta)$  for a two-level atom. This theory predicts full reflection of the probe field for a weak resonant input field covering a half solid angle. Here, interference between the incident beam and the radiated dipole field yields a considerable decrease in the forward mode amplitude [11,27]. For our numerical aperture of 0.4 (i.e.,  $\epsilon = 4\%$ ), we expect a probe beam extinction of 16% using Eq. (1). More refined models were proposed in [10,11,28] that used cylindrical modes and included the dipole emission pattern. This set of modes is adapted to the coupling of the input beam with a high numerical aperture lens beyond the paraxial approximation. From [10], we expect our extinction to be around 13%. We note that for efficient information transfer between a single photon and a single two-level atom, the full dipole radiation pattern and the reversed temporal mode of the atomic emission have to be matched by the single photon input mode [9]. However, for long term and controlled storage, a three-level system may be employed, where the control field can shape the time evolution of the photon emission and absorption processes [1,22].

Our experimental setup and the level scheme of the atom are depicted Figs. 1(a)–1(c). We use a trapped and optically cooled Barium ion in a spherical Paul trap as our single-atom reflector. Two red (649 nm) and green (493 nm) laser fields drive the  $S_{1/2}$  to  $P_{1/2}$  and  $D_{3/2}$  to  $P_{1/2}$  transitions, respectively. The ion is continuously cooled on  $S_{1/2}$  to  $P_{1/2}$  by the 493 nm laser that is red detuned by 50 MHz with respect to resonance. The cooling beam intensity is set far from saturation to minimize depopulation of the  $S_{1/2}$  state, yet allowing cooling to the Lamb-Dicke regime. The saturation parameter obtained by fitting the four dark resonances in the fluorescence spectrum is about 0.1. Here, the saturation parameter is defined for each transition as  $\Omega^2/(\gamma^2 + \Delta^2)$ , where  $\Omega$ ,  $\gamma$ , and  $\Delta$  are the Rabi frequency, spontaneous decay rate, and the laser detuning of the particular transition, respectively. Atomic population from the  $D_{3/2}$  manifold is recycled by the red *repumper no. 1*, red detuned by 35 MHz and operated with a saturation parameter of around 0.8. For this configuration of the laser intensities and frequencies, simulations show that in steady state, 70% of the atomic population is in the  $S_{1/2}(m = +1/2)$  Zeeman sublevel.

The weak probe beam is frequency-shifted with respect to the cooling beam by an acousto-optic modulator and spatially filtered using a single-mode fiber (SMF) to guarantee a Gaussian spatial profile. Its polarization is adjusted by a quarter-wave plate for efficient elastic scattering on the  $S_{1/2}(m = +1/2)$  to  $P_{1/2}(m = -1/2)$  transition.

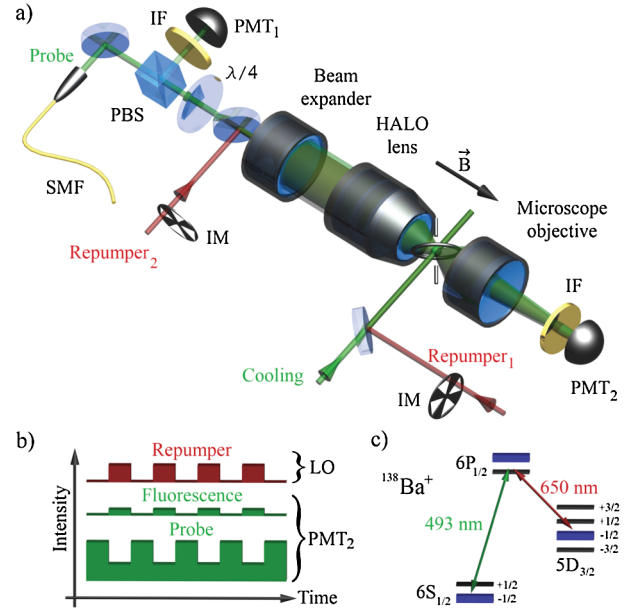


FIG. 1 (color online). (a) Schematic of the experimental setup. PBS: polarizing beam splitter,  $\lambda/4$ : quarter-wave plate, IF: interference filter to select the green fluorescence, IM: intensity modulation, PMT: photomultiplier, and SMF: single-mode fiber. The ion is cooled by the *cooling* beam, while the repumper no. 1 recycles population from the  $D$  state manifold to the  $S_{1/2}$  to  $P_{1/2}$  transition. The *probe* beam is spatially adjusted to match part of the atomic dipole emission profile and is detected on the photomultiplier PMT<sub>2</sub>. In the EIT experiment, the probe field itself serves as a cooling beam and a copropagating repumper no. 2 is used instead. (b) Modulated detection scheme, see text for details. (c) A weak magnetic field  $\vec{B}$  lifts the energetic degeneracy of the Zeeman substates and creates an eight-level system. The levels marked as bold lines were employed in the EIT experiment.

A crucial part of the experiment is to overlap the incoming probe beam with the dipole emission pattern. This mode-matching is done using an expanding telescope and a custom-designed objective [29] with a numerical aperture of 0.4. The transmitted probe together with a 1.5% fraction of the ion's green fluorescence is then collected by a microscope objective and detected on photomultiplier PMT<sub>2</sub>. The green fluorescence is detected in the backward direction by PMT<sub>1</sub>. A typical fluorescence count rate measured on PMT<sub>1</sub> is 600 photons per second, with the fluorescence from the probe contributing to less than 100 photons per second. These count rates are more than 10 times lower than the count rates typically observed for saturating the  $S_{1/2}$  to  $P_{1/2}$  transition.

For precise estimation of our extinction efficiency, we modulate the repumper beam at 600 Hz using a mechanical chopper (IM). With the repumper on, fast optical pumping to the  $S$  state takes place, which allows both scattering of probe and cooling lasers. With repumper off, however, the green cooling beam depopulates the  $S$  state, so that the probe does not interact with the ion. The probe signal intensity is then modulated by the ion with a phase shifted

by  $\pi$  with respect to the chopping signal. The transmission signal from PMT<sub>2</sub> is subsequently demodulated and low pass filtered. As a first step, we find the lock-in reference phase which yields the maximum positive signal amplitude for the fluorescence only, i.e., operating with large cooling field powers and with the probe off. Next we turn down the cooling beam power to below saturation in order to observe a negligible fluorescence signal while still cooling the ion efficiently. With the probe field on, reflection off the ion gives a negative signal [see Fig. 1(b)], thus unambiguously discriminating the fluorescence contribution from the probe extinction.

Figure 2 shows a typical scan of the probe beam extinction as a function of probe frequency. We observed a Lorentzian dependence of the transmission profile with a width of 11 MHz. A maximum of 1.35% extinction was found on resonance. From the maximum ion fluorescence counts that we could mode match to the single-mode fiber, we estimate the coupling to  $\epsilon \approx 0.5\%$ . The expected  $\epsilon = 4\%$  coupling efficiency is reduced by imperfect spatial overlap between the fiber mode and the ion's dipole field, aberrations of the optical system, and atomic motion. Including the 70% pumping preparation to the  $S_{1/2}(m = +1/2)$  Zeeman sublevel, we predict an extinction of 1.4%, in close agreement with the measured value.

We now demonstrate EIT of the ion on the probe light using a dressing laser field on the red transition. Under conditions of a weak probe and stronger control field, a narrow transparency window “opens” for the probe that would otherwise be reflected in the absence of the control laser. This effect was demonstrated by many groups using optically thick atomic ensembles (see Ref. [30] for the first demonstration), but has not been observed using single atoms in free space.

Under weak probe excitation, the probe transmission as a function of the two-photon detuning  $\delta = \Delta_g - \Delta_r$  can be

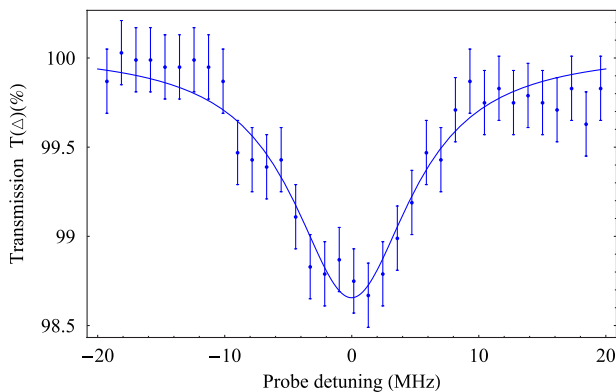


FIG. 2 (color online). Normalized power of a probe field transmitted through a single trapped Barium ion as a function of probe beam detuning. The transmission spectrum is fitted by a Lorentzian profile with a width of 11 MHz. The peak probe beam extinction is 1.35%. The error bars are derived from the rms value of the intensity fluctuations of the probe beam.

found by solving the Bloch equations [18] and using the above input-output relations. Neglecting the angular dependence of the extinction (due to polarization), we can replace the function  $\mathcal{L}$  by

$$\mathcal{L}_\Lambda(\delta) = \frac{\gamma(\gamma_0 - i\delta)}{(\gamma_0 - i\delta)(\gamma + i\Delta_g) + \Omega_r^2}, \quad (2)$$

in Eq. (1), where  $\Omega_r$  is the Rabi frequency of the red laser field,  $\gamma_0$  the ground state dephasing rate, and  $\gamma$  the natural linewidth of the two transitions (assumed to be the same for simplicity). An important condition for EIT to take place is  $\gamma\gamma_0 \ll \Omega_r^2$ , i.e., the pumping rate to the dark state must be much faster than any ground state decoherence process. Independent frequency fluctuations of the two laser fields, magnetic field fluctuations, and atomic motion-induced Doppler shifts, must be therefore reduced. When this is the case, extinction of the resonant probe can be completely inhibited, within a small range of control laser detuning  $\Omega_r^2/\gamma$ , creating an EIT window. This is what we observed in this experiment.

Here, we copropagated the control and probe fields to eliminate the effects of Doppler shifts due to the ion motion. We found that the motion-induced decoherence yields broadening of tens of kHz, which reduced the EIT when the control and the probe were orthogonal to each other. To optimize EIT conditions, we do not use the cooling fields which would reduce the EIT process, so the ion was now cooled by the probe itself. Consequently, a detuned ( $\approx 10$  MHz to the red) and more intense probe was used, which gave extinction efficiencies of about 0.6%. Because of the multilevel structure of Barium, a single three-level system can only be perfectly isolated from the others through optical prepumping. Stark-shifts induced by the other levels and double- $\Lambda$ -type couplings here contribute to a slight reduction of the EIT contrast.

Figure 3(a) shows the probe beam extinction strength as the control field (*repumper no. 2*) is scanned across the two-photon resonance. Here, the saturation parameters of the probe and control field are set to 0.1 and 0.8, respectively. We observe a large inhibition of the probe beam extinction at zero two-photon detuning, with a peak value of 75%. The measured linewidth of the EIT window is 1.2 MHz, much below the natural linewidth of the  $S$  to  $P$  transition. Figure 3(b) shows the resulting scattered light intensity in the backward direction, showing a corresponding decrease of the fluorescence light around the two-photon resonance, as expected due to dark state pumping. Although the ion motion was too large to yield significant extinction on the blue side, the other three EIT profiles could also be observed. The contrast and width of these two-photon resonances are mostly given by power broadening and frequency fluctuations of our two lasers. The control and probe laser linewidths are 80 kHz and 20 kHz, respectively, which allows a minimal EIT transmission linewidth of 82 kHz to be observed. Performing an efficient



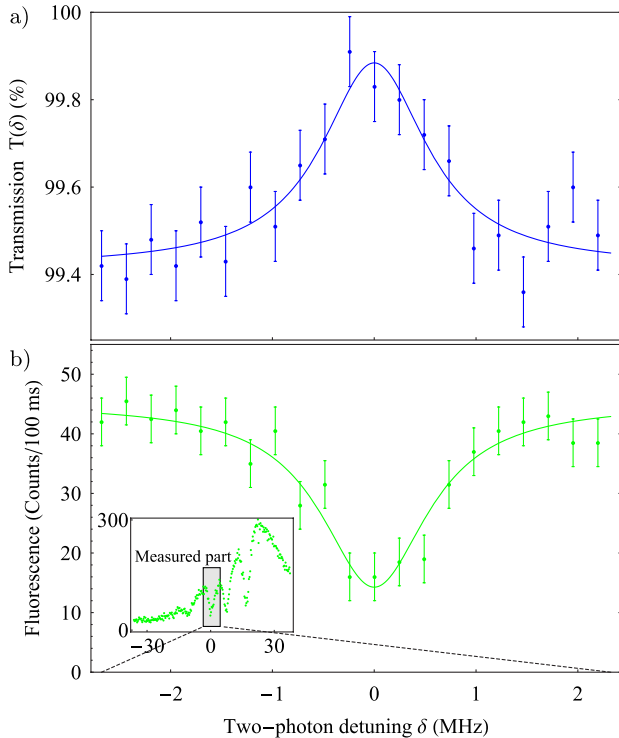


FIG. 3 (color online). Electromagnetically induced transparency and fluorescence spectra. (a) Normalized transmitted power of a probe field scattered by a single ion as a function of two-photon detuning (Here the control laser frequency is scanned). (b) Dark resonance in the fluorescence spectrum measured in the forward and backward directions. The inset shows a typical fluorescence spectrum with all four dark resonances. The EIT experiment was performed on the shaded part of the spectrum, with the levels as indicated Fig. 1(c).

prepumping to the  $S$  state, and switching the cooling fields off while the EIT is measured, would allow us to reach ultranarrow transmission profiles. This is of significant interest as this means that large phase shifts are imprinted on the probe field [30], which might become useful for precision spectroscopy and state detection with single atoms.

In conclusion, we observed both the direct extinction of a weak probe field and electromagnetically induced transparency from a single Barium ion. The amount of extinction of up to 1.35% is limited mainly by the numerical aperture of the coupling lens and imperfect spatial overlap of the incoming field with the atomic dipole pattern. Extinction values of up to 50% are within experimental reach by using a numerical aperture of, say, 0.7 and realizing a better spatial mode matching. We demonstrated inhibition of extinction due to EIT of almost 75%. Better EIT contrasts and narrower features can be reached through efficient preparation of an isolated  $\Lambda$  scheme, with prepumping steps. Our results have a number of direct applications besides precision spectroscopy. One can take advantage of the sensitivity of EIT with regards to Doppler

shifts to read out the atomic motional state in a quantum nondemolition manner, thereby also opening the way towards quantum feedback [31]. Furthermore, the presented results have direct implications for long distance quantum information [1,2]. Quantum memories, where quantum states between atoms and light fields are reversibly exchanged, indeed form an essential part of quantum repeater architectures [2,18] and EIT is a prominent method to achieve such a transfer [18].

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