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Free-space read-out and control of single-ion dispersion using quantum interference

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We perform a free-space measurement and control of the refractive index of a single trapped ion in the presence of quantum interference effects. The single atom refractive index is characterized by the Faraday rotation of a laser field tightly focused onto a trapped and laser-cooled barium ion. It is tuned using the internal ion state that is optically controlled via a V or a Λ scheme. Measurements of the phase shift associated with an electromagnetically induced transparency are then performed and the internal state on the qubit transition is read-out with a detection fidelity of $(98 \pm 1)\%$.

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Coherent manipulation of phase shifts imposed by atoms onto light fields has been a subject of investigations for decades. Besides the classical optics applications, the subject gained interest with the perspective of the coherent control of quantum states of light and matter. Atomic phase shifts allow, for instance, localization of quantum states of light within quantum memories [1], or dispersive read-out of internal [2–4] and external [5] atomic states. Investigating the detailed properties of phase shifts with well-localized atoms and single photons would furthermore yield several direct applications in quantum information science [6,7]. To achieve this, common approaches use optical cavities coupled to a few atoms [8,9] or the coupling of a single light mode to an optically thick column of atoms [10]. A recent research area also investigates direct coupling of light to single atoms in free space using high numerical aperture elements. Recently, single cold rubidium atoms [11], single cold molecules [12,13], and quantum dots [14,15] have been successfully employed to observe effects that were often thought to be specific to high finesse cavities or to atomic ensembles. A 1° phase shift induced by a single Rubidium atom onto a freely propagating probe was, for example, measured in [16].

Single ions are also good candidates for further fundamental investigations of such single-pass light-atom couplings [17–20]. The strong confinement offered by Paul traps and a high numerical aperture system allowed us recently to observe an electromagnetically induced transparency (EIT) from a barium ion [21] as well as its operation as a mirror of a Fabry-Pérot-like cavity [22]. In this Rapid Communication, we perform free-space refractive index measurements of a single trapped ion in the presence of quantum interference effects. This is achieved by tightly focusing a weak detuned linearly polarized laser field onto a single barium ion and by measuring the Faraday rotation of the laser field. We use this tool to measure the atomic refractive index dynamics when a narrow laser drives the adjacent transition in a V scheme and to read-out the state of the single atom qubit with a fidelity of 98%. Last, we alter the single atom refractive index via a quantum interference process and measure the phase shift across the electromagnetically induced transparency spectrum.

Let us first describe how we use Faraday rotation to infer the single-ion phase shifts. Faraday rotation takes place when an optically active material rotates the polarization direction of a linearly polarized input field. In circularly birefringent materials, such as atomic gases in a magnetic field [23–26], the two circular components of the field acquire different phase shifts, the strengths of which depend on the magnetic field amplitude.

Figure 1(a) shows our experimental setup. A barium ion is trapped and cooled in a standard ring Paul trap, and a probe field is tightly focused onto it using a telescope followed by a high-numerical aperture objective in-vacuum [21,22,27]. The numerical aperture is here 0.4, which corresponds to a fraction of the full solid angle $\epsilon \approx 4\%$. A magnetic field of 5 G is applied along the probe field direction and also used here to define the quantization axis. A linearly polarized probe field is then shone on the ion. We estimated that the spatial profile of the probe matches the linear dipole emission pattern very well over the solid angle of interest. Further shaping of the probe intensity profile was then not required [28]. The probe polarization is analyzed using a polarimetric setup and photomultiplier tubes (PMT). In practice, we record the signal using only one detector and a wave plate alternatively tuned at 45° or -45° with respect to the polarizing beam splitter axis.

The level scheme of $^{138}Ba^+$ is shown Fig. 1(b). The probe field is tuned to the $S_{1/2} \rightarrow P_{1/2}$ transition and with our choice of quantization axis, its polarization is decomposed onto left and right circularly polarized modes. The two polarization modes are detuned differently from their transitions and thus experience different indices of refraction. We set the intensity of the probe field well below saturation [21]. The power of the probe field at the ion location is about 10 nW focused down to a few microns, which after about a 30% loss due in part to the 0.5% detection angle of our microscope, corresponds to 200 kcounts/s on the PMT. This is two orders of magnitude lower than the saturation intensity for this transition so elastic scattering always dominates. To provide cooling of the ion, we also use a red detuned 493 nm laser field that is perpendicular to the probe direction and a laser at 650 nm, copropagating with the cooling beam, for pumping out population from the $D_{3/2}$ level. Both are vertically polarized. To precisely measure the polarization rotation signal, we use a locking method where the repumper is amplitude modulated at a rate of 5 kHz. The PMT signal is then demodulated and low-pass filtered with a time constant of 1 s.

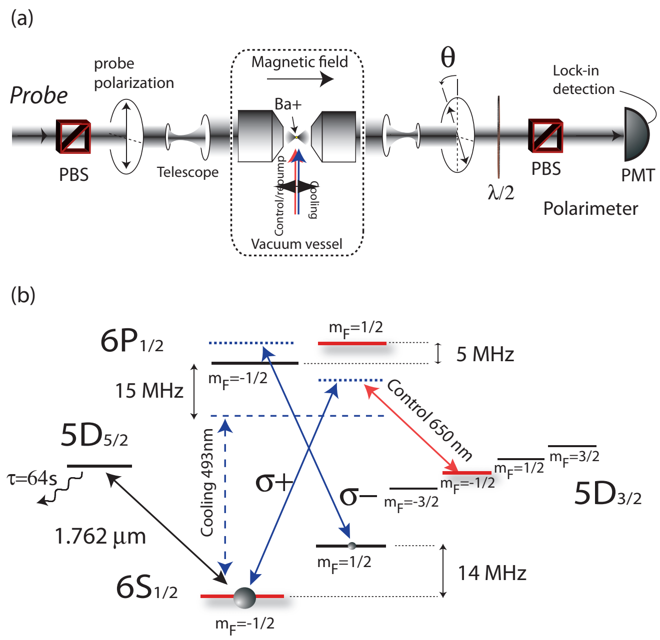

FIG. 1. (Color online) (a) Scheme of the Faraday rotation setup used to measure the EIT phase shift. The probe field is prepared in a horizontally polarized mode after passing through a polarizing beam splitter (PBS). The laser field is then expanded by a telescope and coupled through a high numerical aperture lens in vacuum (numerical aperture $= 0.4$). The single ion rotates the polarization of the light field, which after recollimation is detected by polarimetry. (b) Level scheme of $^{138}Ba^+$ and laser fields used in the experiment. The input probe at 493 nm is decomposed in the circular basis and excites the two branches of the spin-half system with different detunings. A laser field at 650 nm is used for both repumping population from the $D_{3/2}$ level and as the control field in the EIT phase shift measurements. A laser at 1.762 μm is also available to excite the quadrupolar transition from the $S_{1/2}$ to the $D_{5/2}$ level.

The intensity of the light at the PMT can be written as

$$I_{45} = \frac{1}{2}|E^+_{\rm out}e^{i\pi/4} + E^-_{\rm out}e^{-i\pi/4}|^2, \quad (1)$$

where $E^+_{\rm out} = (1 - 2\epsilon\mathcal{L}^+)E_{\rm in}$ and $E^-_{\rm out} = (1 - 2\epsilon\mathcal{L}^-)E_{\rm in}$. The real and imaginary parts of $\mathcal{L}^\pm = \rho_\pm\gamma/(\gamma + i\Delta^\pm)$ correspond to the absorption and phase lag of the two scattered circularly polarized field modes with regards to the input field, respectively. $\Delta^\pm = \Delta \pm \Omega_B$ are the detunings of the σ^+ and σ^- polarized fields from their respective transitions. Δ is the probe laser detuning, defined as the detuning from the $S_{1/2} \rightarrow P_{1/2}$ transitions if they were not Zeeman shifted and Ω_B is the Zeeman splitting. $\rho_\pm$ are the populations in the $S_{1/2}(m = \pm 1/2)$ ground states, respectively. The $\pm\pi/4$ phase shifts are due to the rotation of the probe polarization direction induced by the $\lambda/2$ plate set to 45°. The resulting overall $\pi/2$ phase shift between the two circularly polarized modes allows access to the imaginary part of one of the field amplitudes. To measure the rotation of the polarization angle, we record the total transmission s_0 without the $\lambda/2$ wave plate. After inserting the wave plate, we can access the s_2 Stokes parameter [29] defined as $s_2 = 2I_{45} - s_0$. For our small extinction values the other Stokes parameters $s_1 \approx s_0$. The Faraday rotation

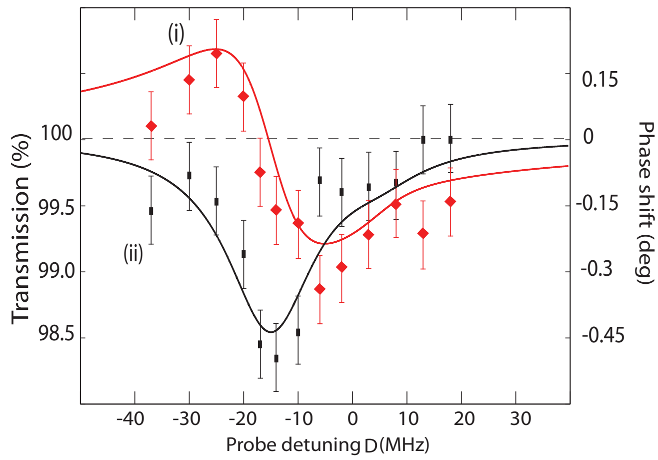

FIG. 2. (Color online) Traces (i) and (ii) show the Faraday rotation angle θ (or phase shift) and the transmission s_0 of the probe laser through the single ion as a function of the laser detuning, respectively. The solid lines show a fit using four-level equations. Error bars correspond to one standard deviation estimated from the Poissonian noise within our detection bandwidth.

angle $\theta \approx (1/2)\arctan(s_2/s_0)$ is directly related to the phase shift induced by the atom. It can indeed be shown that, using the approximation $\arg(1 - 2\epsilon z) \approx -2\epsilon{\rm Im}(z)$ in the limit of small ϵ,

$$\theta = \frac{1}{2}\arg[1 - 2\epsilon(\mathcal{L}^+ - \mathcal{L}^-)], \quad (2)$$

which is the phase lag experienced by the output field with respect to the input. A measurement of I_{45} and s_0 thus provides a measurement of the phase shift acquired by the two circularly polarized modes.

I_{45} and s_0 are first measured as a function of the probe field detuning from the $S_{1/2}$ to $P_{1/2}$ level. For these measurements, the cooling beam was kept on and tuned to one of the two dark resonances that provides efficient pumping to the $S_{1/2}(m = -1/2)$ level while still allowing cooling of the ion at the Doppler limit. The levels that are involved in this so called "dark-state pumping" are marked in red in Fig. 1(b). Figure 2 shows the results of the measurement of θ [trace (i)] and s_0 [trace (ii)] as a function of the probe frequency difference from the $S_{1/2}$ to $P_{1/2}$ level. As can be seen from the measurement of s_0, the dark-state pumping causes a strong imbalance between the two ground states populations. This is manifest in the 1.5% extinction that is seen -14 MHz red detuned from the central line and in the almost completely suppressed extinction for the other mode at 5 MHz. With this dark-state preparation technique, trace (i) displays a clear anomalous dispersive profile across the resonance of the $\Delta m = +1$ transition, and the circularly polarized mode σ^- is almost not contributing. This pumping technique thus allows us to isolate a single two-level atom and to reach a maximum of 0.3° phase shift. We note that the probe field is here too weak to induce any nonlinear optical rotation [23], as is confirmed by the theory. Solid lines show the result of a fit of the data using the above four-levels calculations, with $\epsilon = 0.8\%$, $\Omega_B = 9$ MHz, $\rho_- = 0.9$, and $\rho_+ = 0.1$. With the population $\rho_\pm$ as the only two fitting parameters, good agreement is found with the experimental results. This confirms that we can approximate

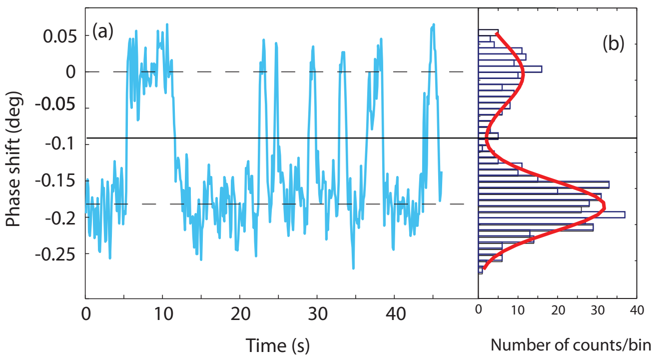

FIG. 3. (Color online) (a) Polarimeter signal as a function of time when the 1.76 μm laser field is tuned to the $S_{1/2} \rightarrow D_{5/2}$ quadrupolar transition. An integration time of 300 ms was used here. Several quantum jumps are observed. (b) Histogram showing the probability of measuring a given phase shift over these 45 s of measurements within a 0.01 bin width.

our level scheme by a four-level system and neglect nonlinear optical rotation effects.

Compared with measurements of phase shifts using Mach-Zehnder interferometers (MZI), our polarization rotation method is a rather simple and precise way of inferring atomic phase shifts. In fact, the technique may still be seen as an interference process between the two polarization states σ^+ and σ^-, which follow the same optical path and then interfere after the wave plate and polarizing beam splitter. Besides providing immediate spatial mode matching of the two polarization modes, another advantage is that any thermal or acoustic noise that might lower MZI signals do not matter here since they are common to both circularly polarized fields.

We now show that the polarization rotation detection method also provides a means of measuring atomic qubits. With a laser at 1.762 μm we are able to perform coherent manipulations on the $S_{1/2}$ to $D_{5/2}$ transitions of barium in a linear Paul trap with the same high numerical aperture optics [30]. Here, by weakly driving this quadrupole transition, and with a time constant of 300 ms for the detection of the phase shift, we can detect changes in the phase shift much faster than the spontaneous decay time of our barium qubit (≈64 s). Figure 3(a) shows the evolution of the phase shift θ during 45 s when a weak 1.76 μm laser is tuned close to the quadrupole transition. The probe frequency is set here to $\Delta = 0$ with a detected count rate of of 200 kHz. We observe that the phase shift is interrupted by sudden quantum jumps which reveal that population is transferred to the $D_{5/2}$ level, thereby completely canceling the polarization rotation. Figure 3(b) shows a histogram where phase shifts values are counted within a 0.01° bin width during the 45-s-long measurement. Two distinct bell-shaped distributions corresponding to two mean coherent state amplitudes are seen. The probability of inferring the correct atomic state is $1/2(p_S + p_D) = (98 \pm 1)\%$ when using the thick solid line as a threshold. $p_{S,D}$ are the probabilities of finding the atom in the $S_{1/2}$ or $D_{5/2}$ level, which are estimated by fitting the histograms by a sum of two Gaussian distributions and by calculating the fraction of population that lies inside the chosen threshold.

At present, the measurement time needed to resolve the atomic state is larger than when using fluorescence detection in the same setup [30], but the method may prove useful for efficient read-out of atomic states in systems where electron shelving techniques are more involved. Our polarization rotation observations can also find applications for the real-time read-out of small magnetic fields. Using, for instance, a radio-frequency field driving the two ground states together with a detection of the polarization rotation at the Larmor frequency would enable active feedback to the magnetic coils for compensating magnetic field noise [31] at the exact location of the single atom and may be simpler than currently existing techniques [32]. Provided modifications of the setup are made, this dispersive read-out of the atomic population has furthermore potential for nondestructive or quantum nondemolition (QND) measurements of atomic superposition. It was argued in [33] that efficient state estimation without spontaneous emission cannot be reached with a free-space read-out only and that a cavity has to be placed around the atom to be within such a QND regime [2,33]. A tantalizing option for us would be to use a single distant mirror [22,27] or a low finesse cavity, for which using slightly higher numerical aperture lenses would enable entering the QND regime. These ideas will be investigated in the future.

Moreover, the Faraday rotation technique allows us to investigate the dependence of the single atom induced phase shift in the presence of quantum interference effects. In the above measurements, the cooling and repumping beams were tuned to a dark resonance in order to provide prepumping to one of the $S_{1/2}$ levels. As in [21], we now turn off the transverse cooling beam and cool with the linearly polarized probe field itself. This lowers the overall extinction but enables the probe and control to coherently interact in the Λ scheme. The probe is tuned 10 MHz to the red. In such a configuration the probe undergoes an EIT [21] where the population in the excited state of the Λ scheme [see Fig. 1(b)] is canceled due to a quantum interference between the two excitation pathways leading to the $P_{1/2}$ excited state. Figure 4 trace (i) shows the result of the measurement of the probe transmission versus the two-photon detuning δ. δ is scanned by changing the frequency of the red laser across the dark resonance shown in Fig. 1(b), the intensity of which is set close to saturation. In this EIT regime, a rapid change of the transmission is found as a function of the two-photon detuning δ, and an almost complete cancellation of the transmission is measured at $\delta = 0$. Associated with such a steep change of the probe transmission, we also expect a fast roll-off of the phase with the opposite slope than for the extinction phase slip. Figure 4 trace (ii) shows the measurement of θ, using the same polarimetric technique as for the previous four-level scheme measurements. Here again, close to the dark resonance, the Faraday rotation angle yields the phase shift induced by the atom. The clear dispersive shape of θ across the two-photon resonance is here a sign of the EIT induced phase shift from the ion where a maximum phase lag of 0.3° is observed with the expected slope sign. The solid lines show a fit to the experimental results using eight-level Bloch equations where we replace the two-level atom Lorentzian functions $\mathcal{L}^{\pm}$ in Eq. (2) by newly found susceptibilities. The theory describes well the data with the repumping and probe field intensities as the only two free parameters. The measured

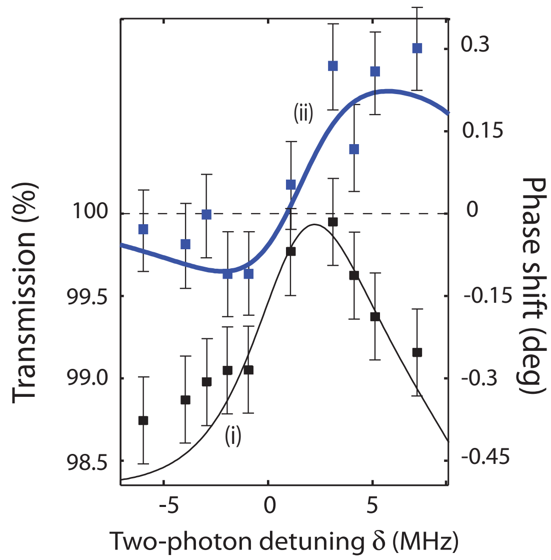

FIG. 4. (Color online) Electromagnetically induced-transparency transmission and phase shifts from the single atom as a function of the probe laser detuning (blue and black points). The solid lines show a fit using eight-level Bloch equations.

asymmetry of the dispersion and transmission profiles is due to a slight overlap with neighboring dark-resonances and our detuned driving of the Λ scheme. The distinctive feature of this interference effect is that the flipping of the phase shift sign occurs only over a couple of MHz. Increasing further the slope steepness can in fact be done by performing the experiment with a smaller probe and repumping powers which can be implemented by appropriate switching of the laser cooling beams involved the experiment. Achieving a very steep phase shift dependence across the atomic spectrum would open the way for reading out the motional [5] and internal [34] energy of the atom.

In conclusion, we demonstrated a free-space control and read-out of the dispersion of a single ion. Tightly focusing a weak detuned linearly polarized probe field onto a barium ion and further tuning of the atomic population were shown to provide an effective means of measuring single atom phase shifts. We could observe the steep phase change across the electromagnetically induced-transparency spectrum. Phase shifts of 0.3° were measured, limited mostly by the finite numerical aperture of the employed detection optics. Last, we use the phase measurements for the high fidelity read-out of the single atom state by inducing quantum jumps with a narrow laser beam tuned to a long lived optical transition. Besides demonstrating further the potential of free-space coupling to single ions for fundamental quantum optics and quantum information science, these experimental results will trigger interest for quantum feedback to the motional state of single atoms, as proposed in [5] using EIT, for the dispersive read out of atomic qubits and for sensitive single atom magnetometery [23,31].

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