

Phase Shift of a Weak Coherent Beam Induced by a Single Atom

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We report on a direct measurement of a phase shift on a weak coherent beam by a single ^{87}Rb atom in a Mach-Zehnder interferometer. By strongly focusing the probe mode to the location of the atom, a maximum phase shift of about 1° is observed experimentally.

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Introduction.—While photons are the ideal carriers for transporting quantum information over long distances, atoms can be used to store and process information. Thus, atom-photon interfaces will be important for implementing more complex quantum information processing tasks [1,2]. The efficiency of information exchange between photonic “flying” qubits and atoms or similar microscopic systems requires a strong interaction between them, characterized, e.g., by the scattering probability of a single photon. The traditional method to bring this probability close to unity is to place an atom into high finesse cavity [3,4], where, in a simplified picture, a photon visits the atom many times and hence increases its chance of being scattered. Recently, however, it was shown that efficient scattering can also be achieved without cavity assistance by strong focusing, localizing the field of the photon to a small region near the scatterer [5,6]. A high scattering probability of photons has been demonstrated experimentally for various microscopic systems [7–9].

Apart from the power changing aspect of the scattering process, the presence of the single atom in a focus of the light beam can also change its phase. This may help to realize a photonic phase gate, in which the phase of a photon is changed depending on the presence or the internal state of the atom [10]. In such a scenario, the atom can be viewed as a mediator for photon-photon interactions due to the nonlinear dispersion. This nonlinear phase shift has been investigated in experiments involving cavities [11,12] and atomic ensembles [13]. It is interesting to perform a similar experiment with a strongly focused optical mode, because of its much reduced complexity compared to cavity QED experiments.

As a first step towards such an element, we report here on the direct measurement of the phase shift the presence of a single ^{87}Rb atom imposes on a strongly focused coherent light field in a Mach-Zehnder interferometer. There, the probe passes only once through the atom localization volume. Following [5,14], a simple theoretical model is used to describe the experimental results.

Experimental setup.—Figure 1 shows a sketch of our experiment. A probe beam is sent through a stabilized Mach-Zehnder interferometer (MZI). One arm contains a

single ^{87}Rb atom, trapped at the focus of a confocal aspheric lens pair (atom arm) in an ultra high vacuum chamber, while the other arm serves as a phase reference.

The probe is a weak coherent beam with a transverse Gaussian profile with an initial waist $w_L = 1.1$ mm at the focusing lens with focal length $f = 4.5$ mm. In the experiment, we tune the probe frequency across the resonance of the $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F' = 3$ transition of the $D2$ line (780 nm). The ratio of optical power in both arms of the interferometer is controlled with a half-wave plate and a polarizing beam splitter (PBS) to match at the input ports of the nonpolarizing beam splitter (BS) without an atom in the focus. A quarter-wave plate preceding the focusing lens prepares the probe into right circular polarization to maximize interaction with the atom [9], before it is focused to a (nominal) waist $w_f \sim 1.0$ μm . After the lenses, the polarization of the probe is converted back to linear to match the polarization of the reference arm. The output modes of the interferometer are then collected into single mode fibers with an efficiency of $\approx 84\%$ without an atom in the trap, which guide the light to silicon avalanche photodetectors Dc and Dd.

The single ^{87}Rb atom is localized at the focus of the aspheric lenses by means of a far off-resonant optical dipole trap formed by a tightly focused light beam at 980 nm, such that there is either one or no atom in the trap at any time due to the “collisional blockade” mechanism [15]. Cold atoms are loaded into the dipole trap from a magneto optical trap (MOT), and the presence of one and only one atom in the trap is verified by observing strong photon antibunching in the second-order correlation function $g^{(2)}(\tau)$ of the atomic fluorescence.

The atom has a small probability to end up in the $5^2S_{1/2}, F = 1$ ground state. To bring the atom back to the probe transition, light resonant to the $5^2S_{1/2}, F = 1 \rightarrow 5^2P_{1/2}, F' = 2$ transition of ^{87}Rb (795 nm) is added to the probe beam, and later removed with an interference filter IF.

The phase stability of the interferometer over the measurement time is ensured by locking it to an off-resonant laser ($\lambda = 830$ nm) copropagating with the probe, and keeping the MZI close to zero optical path difference.

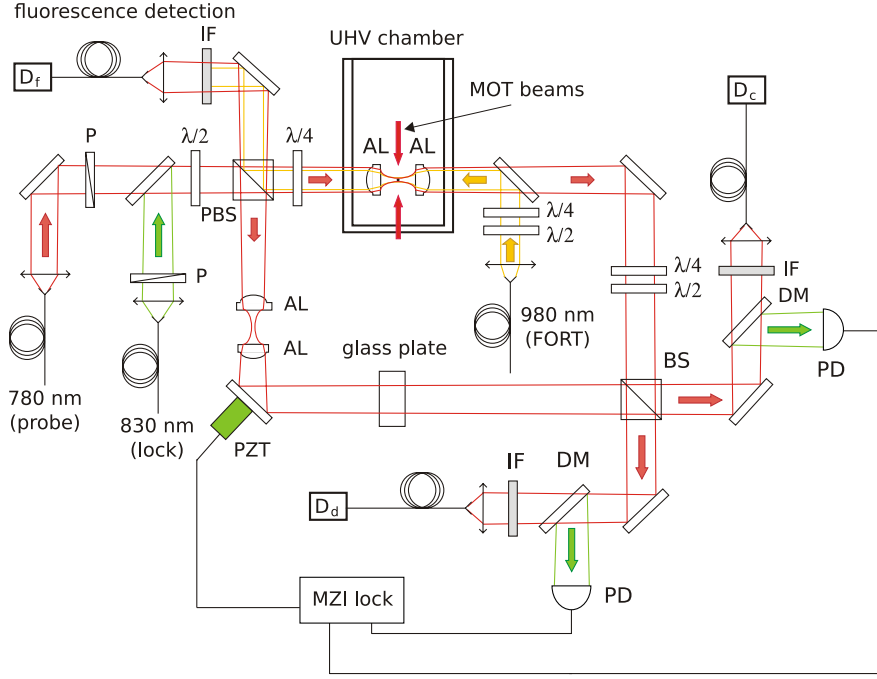


FIG. 1 (color online). Experimental setup. A single atom located by a far-off-resonant trap in a confocal arrangement of two aspheric lenses (AL) is made part of a stabilized Mach-Zehnder interferometer. Refer to the text for explanation of the different components.

This auxiliary light is separated from the probe with dichroic mirrors DM to provide a feedback signal to a piezoelectric actuator (PZT).

To keep the analysis of the interference pattern simple, we aimed for a maximal interference contrast in the MZI. Essential for this is a match of the wave fronts in probe- and reference arm on the output beam splitter of the MZI. A confocal lens pair identical to the one in the probe arm was inserted in the reference arm, with an adjustable separation to compensate for any difference in divergence. The interference contrast (after coupling into the single mode fibers) had a visibility of $V = 98.0 \pm 0.2\%$.

Phase measurement.—Once an atom is loaded into the trap (verified by detecting its fluorescence with detector Df), the MOT beams and quadrupole coil currents are switched off, and the atom is optically pumped into the $5^2S_{1/2}$, $F = 2$, $m_F = -2 \rightarrow 5^2P_{3/2}$, $F' = 3$, $m_F = -3$ closed cycling transition by the same probe beam for 20 ms (see [9] for details). Then detection events at Dc and Dd are recorded for 130–140 ms. After that, the MOT beams are turned on for about 20 ms to check if the atom is still in the trap. If this is the case, the MOT beams are turned off again and the pump, probe and detection sequence is repeated. Otherwise, the last single probe result is ignored, and the interferometer outputs are observed *without* an atom in the trap for 2 s with the MOT beams switched off as a background measurement.

Since our observation is done by detectors probing the light in single mode optical fibers behind beam splitter, we can express all interference effects in terms of scalar amplitudes E of field modes in these fibers, which in the free space part both overlap with the probe and reference mode. The optical powers P_c and P_d in the fibers—in the absence of the atom and up to a constant—are given by

$$P_{c,d} = \frac{1}{2}[|E_a|^2 + |E_b|^2 \pm 2|E_a||E_b|\cos\phi_{ab}], \quad (1)$$

where E_a and E_b correspond to field amplitudes (with the spatial profile of the collecting modes) in the atom or reference arms, and ϕ_{ab} is the phase difference between MZI arms. The interferometer has a maximal phase sensitivity $\partial P/\partial\phi_{ab}$ for $\phi_{ab} = \pm 90^\circ$ where $|E_a| = |E_b|$. Note that this does not imply equal count rates N_c and N_d of the detectors behind the single mode fibers due to the different coupling efficiencies in each channel, and different detector dark count rates. It can be shown that the locking point with the highest sensitivity for a phase measurement with these different coupling efficiencies corresponds to count rates

$$N_{c,d}^l = \frac{N_{c,d}^{\max} - N_{c,d}^{\min}}{2} + B_{c,d} \quad (2)$$

at the output of an empty interferometer, with $N_{c,d}^{\min,\max}$ corresponding to the minimal/maximal observed rates for all phases ϕ_{ab} , and detector background rates B_c and B_d .

An atom in the trap then scatters photons out of the probe beam, causing a power drop in the atom arm. With the same convention as in Eq. (1), the power levels at the output of the MZI are given by

$$P'_{c,d} = \frac{1}{2}[|E'_a|^2 + |E_b|^2 \pm 2|E'_a||E_b|\cos\phi'_{ab}], \quad (3)$$

where $|E_b|$ remains unchanged, and the primes indicate changed values in the atom arm. The phase difference between the arms is given by

$$\phi'_{ab} = \arccos\left(\frac{P'_c - P'_d}{(P_c + P_d)\sqrt{T}}\right), \quad (4)$$

where T is the transmission of the probe beam in the atom

arm,

$$T = \left| \frac{E'_a}{E_a} \right|^2 = \frac{2(P'_c + P'_d)}{P_c + P_d} - 1. \quad (5)$$

Note that for the relations in Eqs. (4) and (5) to hold, $|E_a| = |E_b|$, which we verified by the high visibility of the empty interferometer. The actual phase shift induced by the atom is then simply

$$\delta\phi = \phi'_{ab} - \phi_{ab}. \quad (6)$$

The optical powers $P_{c,c',d,c'}$ leading to ϕ'_{ab} and ϕ_{ab} depend on the corresponding detector events $N_{i,i'}$ via $P_{i,i'} = (N_{i,i'} - N_i^{\min}) / (N_i^{\max} - N_i^{\min})$ to account for dark counts and different efficiencies.

In the same experimental run (i.e., for the same detuning of the probe frequency), we have also performed an independent measurement of the transmission T of the probe beam with the reference arm blocked using the same measurement sequence, which leads to a better signal/noise ratio.

Theory.—The electric field at the input of the beam splitter $\vec{E}'_a(\vec{r})$ results from the superposition of the field of the probe $\vec{E}_a(\vec{r})$ with the field scattered by the atom $\vec{E}_{sc}(\vec{r})$:

$$\vec{E}'_a(\vec{r}) = \vec{E}_a(\vec{r}) + \vec{E}_{sc}(\vec{r}) \quad (7)$$

The spatial dependence of the scattered field $\vec{E}_{sc}(\vec{r})$ is that of a rotating electrical dipole, with an amplitude proportional to the exciting electrical field amplitude E_A at the location of the atom. Far away from the dipole ($r \gg \lambda$), it takes the form [5,6]

$$\vec{E}_{sc}(\vec{r}) = \frac{3E_A e^{i(kr + \pi/2)}}{2kr} [\hat{\epsilon}_+ - (\hat{\epsilon}_+ \cdot \hat{r})\hat{r}] \frac{i\Gamma}{2\Delta + i\Gamma}, \quad (8)$$

where $\hat{\epsilon}_+$ is the unit vector of circular polarization. The frequency-dependent phase enters via the Lorentzian function (Δ is the detuning from resonance, Γ the natural linewidth of the atomic transition). The $\pi/2$ phase reflects the lag of the atom response with respect to the excitation field E_A by $\pi/2$ on resonance.

The superposition of the probe and atomic response leads to an amplitude E'_a in the collection mode. Following [5], we assume that the collection mode $\vec{G}_a(\vec{r})$ coincides with the probe mode, i.e., $\vec{G}_a(\vec{r}) \propto \vec{E}_a(\vec{r})$. With the normalization $\int [\vec{E}_a(\vec{r}) \cdot \vec{G}_a^*(\vec{r})] dS = E_a$, where dS is an element of the integration surface parallel to the local wave front of the probe mode somewhere after the atom, E'_a is given by

$$E'_a = \int [(\vec{E}_a(\vec{r}) + \vec{E}_{sc}(\vec{r})) \cdot \vec{G}_a^*(\vec{r})] dS. \quad (9)$$

Phase shift and transmission of the probe beam are only determined by the complex ratio E'_a/E_a . The extension of the result for Gaussian mode profiles presented in [5] with the Lorentzian term leads to

$$\frac{E'_a}{E_a} = 1 - \frac{R_{sc}}{2} \frac{i\Gamma}{2\Delta + i\Gamma}, \quad (10)$$

where R_{sc} is the scattering ratio for the probe which depends only on a focusing strength $u := w_L/f$ of the Gaussian beam. The atom-induced phase shift of the probe mode is then given by

$$\delta\phi = \arg(E'_a/E_a). \quad (11)$$

Figure 2 shows the dependence of the expected phase shift on the focusing strength u . A maximal phase shift of about 30° at $\Delta = -\Gamma/2$ is expected for this “fiber-atom-fiber” interface for $u = 2.24$. Our experimental parameters correspond to $u = 0.244$ or $R_{sc} = 0.16$, so we expect a maximal phase shift of 2.3° at detuning $\Delta = \Gamma/2$.

Results and discussion.—Figure 3 shows the experimentally observed phase shift and transmission of the probe beam as a function of detuning from the natural resonant frequency. Our transmission results can be modeled by the expression obtained from Eq. (10),

$$T = \left| \frac{E'_a}{E_a} \right|^2 = 1 - \frac{\Gamma^2 R_{sc} (1 - R_{sc}/4)}{4(\Delta - \Delta_0)^2 + \Gamma^2}, \quad (12)$$

with fit parameters $\Gamma/2\pi = 8.20 \pm 0.47$ MHz, $\Delta_0/2\pi = 35.1 \pm 0.2$ MHz, and $R_{sc} = 0.064 \pm 0.004$. The latter is not only governed by the focusing parameter, but also experimental uncertainties about the exact field in the focus and the atomic position, while Δ_0 reflects the trap-induced ac Stark shift. The transmission linewidth Γ slightly exceeds the natural linewidth $\Gamma_{\text{nat}}/2\pi = 6$ MHz of the atomic transition. One reason for this is the finite linewidth of the probe laser, measured as $\Delta\nu_L = 750$ kHz FWHM. Another contribution is Doppler broadening and a position-dependent detuning due to residual motion of the atom in the trap.

The solid line shown together with the phase shift results in Fig. 3 corresponds to Eq. (11), with the parameters Γ , Δ_0 , and R_{sc} from the transmission fit, in good agreement

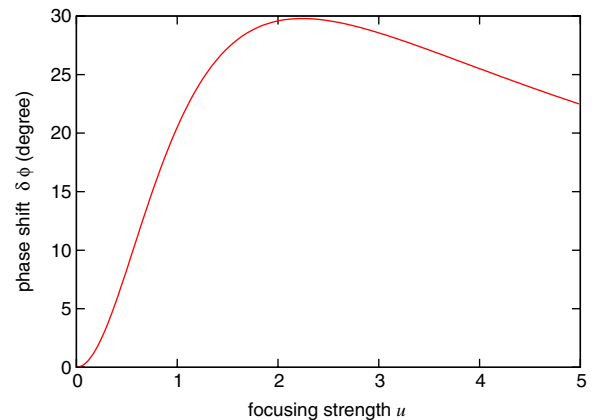


FIG. 2 (color online). Phase shift $\delta\phi$ of a beam with Gaussian profile and focusing strength u (as defined in the text) due to a single atom at a detuning $\Delta = -\Gamma/2$ from resonance. A maximal phase shift of 29.78° is expected for $u = 2.24$.

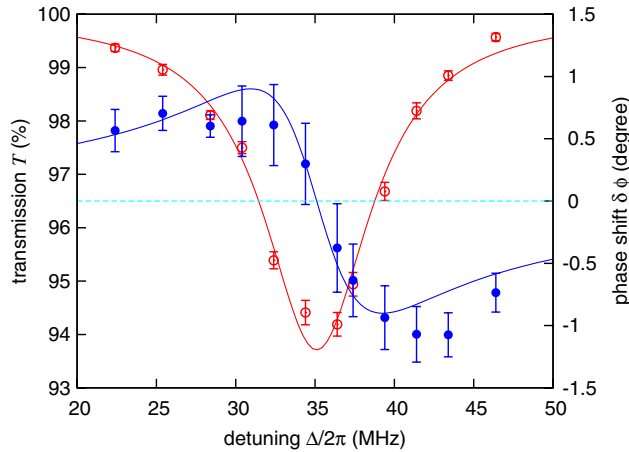


FIG. 3 (color online). Phase shift $\delta\phi$ observed on a weak coherent probe beam tuned across the resonance of a single atom (filled symbols), showing the dispersive character from phase retardation below resonance to phase advancement above resonance. The transmission T of the same probe is shown for reference (open circles). Solid lines correspond to theoretical values (see text for details). Each data point is an average over 100 trapping/calibration cycles, and error bars reflect propagated Poissonian counting statistics.

with the experimental values. As expected, above the atomic resonance an advance of the phase is observed, while below resonance the atom introduces a phase lag to the probe beam.

The maximal phase shift of 0.97° according to Eq. (11) and the fit parameters from the transmission measurement at $\Delta = \Gamma/2$ is about 2.6 times smaller than what we would expect for our focusing parameter. We ascribe this discrepancy to two contributions: firstly, the lenses in the experiment are not ideal, so the calculated value of R_{sc} may not reflect the actual field strength at the atom. An independent measurement of the field at the focus [16–18] would help to assess this contribution quantitatively. Secondly, the atom in the trap is not stationary, thus the average probe field strength that it experiences is lower than the calculated value in the focal position. With our trap frequencies of $\nu_t \approx 70$ kHz in transverse and $\nu_z \approx 20$ kHz in longitudinal direction together with the estimated temperature of the atom of ≈ 100 μ K (as measured in similar trap configurations [19,20]), the atom has a position uncertainty of $\sigma_t \approx 220$ nm and $\sigma_z \approx 780$ nm, respectively, reducing the scattering ratio R_{sc} by 23% [5]. However, the scattering ratio is very sensitive to temperature of the atom, and doubling of the temperature alone would explain the discrepancy between theory and experiment. Additional cooling techniques [20–22] would help to reduce this contribution.

Conclusion.—In summary, we have measured the phase shift that the presence of a single ^{87}Rb atom imposes on a near resonant focused light field. The theoretical model suggests that realistic experimental improvement in the

focusing strength and on the atom localization to levels comparable to what is achieved in ion traps will lead to substantial phase shifts on a light beam by a single atom. With a control of the atomic state by another photon, this atom-light interface may form a relatively simple building block in a phase gate between photonic qubits.

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