Vacuum-Field Level Shifts in a Single Trapped Ion Mediated by a Single Distant Mirror

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A distant mirror leads to a vacuum-induced level shift in a laser-excited atom. This effect has been measured with a single mirror 25 cm away from a single, trapped barium ion. This dispersive action is the counterpart to the mirror's dissipative effect, which has been shown earlier to effect a change in the ion's spontaneous decay [J. Eschner *et al.*, Nature (London) **413**, 495 (2001)]. The experimental data are well described by eight-level optical Bloch equations which are amended to take into account the presence of the mirror according to the model in U. Dorner and P. Zoller, Phys. Rev. A **66**, 023816 (2002). Observed deviations from simple dispersive behavior are attributed to multilevel effects.

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Classically, it is well understood how the radiative damping of an oscillating charge leads to the Lorentzian line shape of emitted radiation [1]. Early quantum mechanical treatments of the spontaneous decay of an atom, however, accounted for natural linewidths by invoking the concept of a zero-point energy or vacuum field [2,3]. The physical notion of a vacuum field with dynamics independent of the radiating atom was propounded by Welton [4], and that changes in this field could be observable was noted by Purcell [5]. While the vacuum field is an intuitive and useful concept in explaining many phenomena in electrodynamics, including such fundamental effects as the Lamb shift and the Casimir force, it has been recognized that spontaneous decay can be interpreted as being induced by a combination of vacuum field fluctuations and the atom's own radiation reaction, the magnitude of the two contributions depending on the chosen ordering of operators [6].

An excited-state atom near a mirror, which is the focus of this Letter, was first treated explicitly by Morawitz [7] who showed classically and quantum mechanically how the presence of the mirror leads to a modified damping rate and to a change in the resonance frequency of the atom. This treatment is formally equivalent to earlier work by Lyuboshitz who considered the scattering of radiation by two dipole centers [8]. Arrays of dipoles are used, for example, in the design of directed antennas in the radio wave range, and similar ideas now form the basis of photonic band-gap materials. Extensive QED studies were performed by Barton [9] who also considered ground state shifts which are, however, of a fundamentally different nature to the resonant radiative shifts of this Letter [10]. The modification of the spontaneous decay rate and the excited-state energy shift induced by a mirror can be attributed in equal amounts to vacuum fields and radiation reaction [11,12], which leads to a transparent interpretation and an intuitive reconciliation with the classical theory [13–15].

Since the first experimental observation of modified spontaneous decay [16], the study of changes in the magnitude and spectral composition of atomic resonance fluorescence due to the presence of nearby dielectric boundaries has developed to a high level of technical control. Seminal experiments with atomic beams traversing optical resonators [17] or Rydberg atoms in microwave cavities [18] are now being continued into the domain where single atoms are transiently stored in high-finesse resonators [19,20], and cavity-induced cooling has been observed [21]. Unlike these experiments with two-mirror cavities and nonlocalized atoms, in this Letter we report on the effect of only a single mirror, which is some 25 cm away, on a single trapped $^{138}Ba^{+}$ ion which is localized much better than the optical wavelength.

Recently, single ions have been trapped inside optical cavities and shown to interact deterministically [22,23] and coherently [24] with the cavity field. The action of a single mirror has previously been shown to lead to position-dependent enhanced and inhibited spontaneous decay [25]. In addition to this dissipative effect, here we report the dispersive action of the mirror, an energy shift of the excited atomic level, which is found to be in accordance with a theoretical treatment of the experimental setup [26], and which furthermore shows some peculiar multilevel features.

The experimental setup and partial level scheme of $^{138}Ba^{+}$ are shown in Fig. 1. A single $^{138}Ba^{+}$ ion is confined in a miniature Paul trap with radial and axial secular frequencies of about 1 and 2 MHz, respectively. Narrow band tunable lasers at 493 nm (green) and 650 nm (red) drive the $^2S_{1/2}$ to $^2P_{1/2}$ and $^2D_{3/2}$ to $^2P_{1/2}$ transitions and Doppler cool the ion. Laser frequencies are set close to resonance and laser intensities are around saturation. A macroscope lens L1 (f-number 2) collects part of the resonance fluorescence, the green photons of which are detected on PMT1 at count rates around 15×10^3 cps.

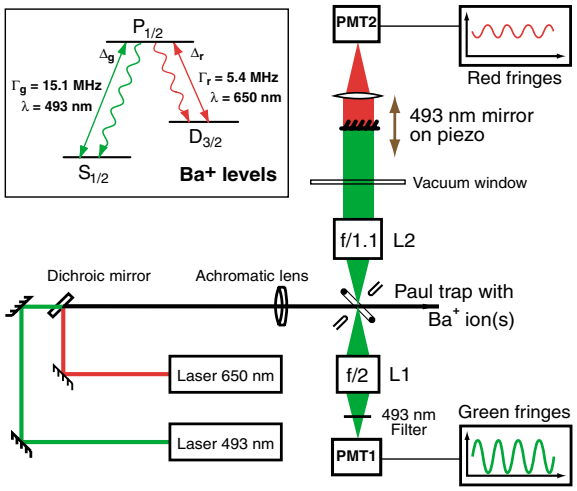

FIG. 1 (color online). Schematic of the experiment and relevant energy levels of Ba^+. Two lasers at 493 nm (green) and 650 nm (red) excite a single trapped Ba^+ ion continuously. The photons on the photomultipliers PMT1 and PMT2 are counted in 0.1 s intervals. Further details of the laser systems and the setup are found in [25,27,28].

The resonance fluorescence emitted into the opposite direction is collimated by lens L2 (f-number 1.1, wavefront abberations $<\lambda/5$). The green part of this signal is retroreflected by a piezomechanically adjustable plane mirror, while the red part is transmitted and detected on PMT2 at around 25×10^3 cps.

Lens L2, situated inside the vacuum chamber, and the retroreflecting mirror, situated about 25 cm away from the ion, are arranged such that they image the ion onto itself, i.e., the returning light is brought to a focus at the position of the ion. The ion and its mirror image can be observed visually through L1. Overlapping the mirror image with the real ion leads to high-contrast interference fringes at PMT1 upon scanning the ion-mirror distance with a piezomechanical actuator [25]. Fine adjustment of the overlap is critical in obtaining high-contrast interference fringes. Disappearance of the interference pattern upon tilting the mirror indicates that the retroreflected beam is focused at the position of the ion to within 2 μm. The green fringe contrast can be as high as 72%, limited by the optical setup (mirror and window flatness, quality of L2), by the thermal motion of the ion [29] and by acoustic noise between the trap and the external mirror.

Simultaneously with the green signal on PMT1 we record on PMT2 the red fluorescence transmitted through the mirror. Varying the mirror-ion distance, which gives rise to the 493 nm fringes, is also seen to modulate the red light with the same period [25]. Note that this modulation is not an interference at the red wavelength, as this would lead to a different modulation period. The reason for the red fringes is the back action of the mirror on the atom; i.e., the mirror modifies the vacuum field at the green wavelength and leads to enhancement and inhibition of spontaneous decay from the $P_{1/2}$ state. As a consequence, the population of the $P_{1/2}$ level is modulated. Since the mirror reflects only the radiation at 493 nm, only the decay constant on the $^2S_{1/2}$ to $^2P_{1/2}$ transition is modified, its variation being proportional to the green fringes. In contrast, the detected red light is a measure of the P-state population, thus revealing the back action of the mirror on the atom. Then one could naively expect that enhancement of spontaneous decay at 493 nm leads to increased depopulation of the upper state and a decrease in the rate of detected 650 nm photons, while inhibited decay at 493 nm increases the 650 nm count rate. However, instead of such anticorrelation, we observe a phase between the green and the red modulation which varies with the laser detuning and takes all values between correlation (phase close to 0 or 2π) and anticorrelation (phase π).

A plot of this correlation phase as a function of the detuning of the red laser is shown in Fig. 2. For large negative or positive detunings, the green and red fringes are in phase, while with the red laser close to resonance, anticorrelation is observed. As we will show now, this dependence of the correlation phase is a direct consequence and an experimental verification of the energy

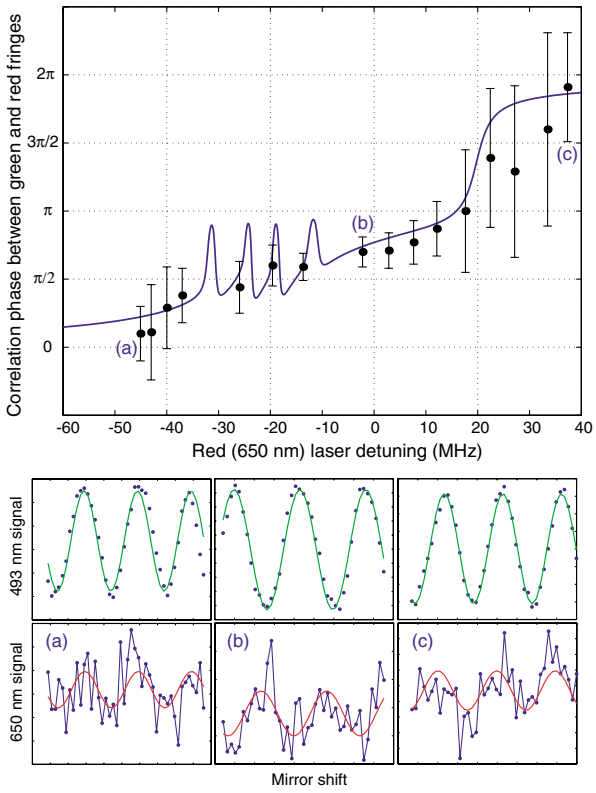

FIG. 2 (color online). Large graph: Correlation phase between the observed fringes in the green and in the red fluorescence vs detuning of the red laser. The line is a calculation using eight-level Bloch equations. The narrow peak structures are caused by dark resonances [27,30]. For the three data points marked (a), (b), (c), the smaller graphs display the simultaneously recorded green (top) and red (bottom) fringes, showing how the correlation phase varies between 0 and 2π.

shift of the $P_{1/2}$ state which goes along with its modified decay rate.

We describe the dynamics of the laser-driven barium ion by optical Bloch equations. In the presence of a magnetic field the degeneracy of the S, P, and D states is lifted so that a realistic model requires all eight Zeeman sublevels to be taken into account [30]. Without the action of the mirror, the eight-level Bloch equations are routinely used to determine the saturation parameters of each laser and the detuning of the 493 nm laser, from an excitation spectrum as the detuning of the 650 nm laser is scanned over resonance; see Ref. [27]. Within this model the decay constants on the green and red transitions are given by Γ_g and Γ_r, and the detunings of the 493 and 650 nm lasers by Δ_g and Δ_r, respectively. To account for the action of the mirror, the model is amended according to the results of Ref. [26]: the decay constant on the $P_{1/2}$ to $S_{1/2}$ transition is modified as

$$\Gamma_g \rightarrow \Gamma_g[1 - \varepsilon \cos(2kl)], \tag{1}$$

and the detunings become

$$\Delta_{g,r} \rightarrow \Delta_{g,r} - (\varepsilon\Gamma_g/2)\sin(2kl), \tag{2}$$

where ε is the effective fraction of a 4π solid angle subtended by L2 [31], $k = 2\pi/493$ nm, and l is the ion-mirror distance. It is easily seen that Eq. (2) actually represents an energy shift of the $P_{1/2}$ level. The shift is independent of the laser intensities; i.e., it remains even when the lasers are switched off. Thus it is not explained by a real ac Stark shift due to the back-reflected 493 nm photons. Instead, its dependence on ε shows that it is caused by the mere presence of the mirror and the associated modification of the vacuum field and of the radiation reaction of the atom. Our value of $\varepsilon \approx 2\%$ implies a level shift of approximately ± 150 kHz.

The correlation phase calculated from the amended Bloch equations is plotted in Fig. 2. It describes well the experimental data. In particular, it must be noted that without the level shift correction of Eq. (2), the calculated dependence would have no other values than π or 0. This can also be seen from an expansion of the excited-state population $\mathcal{P}_P$ for small ε, which leads to an expression of the form

$$\mathcal{P}_P = A_1 + \varepsilon[A_2 \cos(2kl) + A_3 \sin(2kl)], \tag{3}$$

where the quantities A_1, A_2, A_3 depend on the laser intensities and detunings [26]. Without a level shift, the factor A_3 would vanish and the signals would always be (anti)correlated.

The data in Fig. 2 represent 7 h of near-constant interrogation of a single barium ion. For each 650 nm laser detuning, up to 80 green and red interference periods were recorded simultaneously while the ion-mirror distance was varied. The correlation phase was then determined from the data afterwards. The 493 nm laser is stable to about 1 MHz over long periods while a red laser reference cavity drift rate of ~ 2 MHz/h limited the accuracy to which the 650 nm laser detuning could be determined. The data in Fig. 2 have detunings accurate to within ± 1 MHz.

The red fringe contrast also varies with red laser detuning. It reaches values up to 2.5%, but for the laser parameters used in the data of Fig. 2, it goes to a minimum for $\Delta_r \approx +20$ MHz. This, in conjunction with poor Doppler cooling at positive detunings, accounts for the large measurement errors in the correlation phase in this regime. The measured variation of red fringe contrast is shown in Fig. 3. From a comparison with the expected dependence, again calculated with the Bloch equations, we estimate that optimally the mirror subtended an effective solid angle of $\varepsilon = 3.2\%$ of 4π, but the typical value is about 2%.

While all observations are well described by the model, thus verifying that the level energies and decay rates are indeed modified by the distant mirror, we also find peculiar features which are due to the multilevel structure of the atom and would not appear in a simple two-level system. The red fringe contrast can fall completely to zero for a specific positive detuning of the 650 nm laser and a particular ratio of the laser intensities. In other words, modification of the decay constant on the green transition may have no effect on the excited-state population. If from that particular set of parameters, the red laser intensity is increased further, the dispersive dependence of correlation phase vs detuning shown in Fig. 2 changes shape. At large positive Δ_r it is seen to return to zero instead of going up to 2π. An example is displayed in Fig. 4. While it can be suspected that an interplay of modified decay and optical pumping is responsible for this behavior, the detailed underlying causes are the subject of future study.

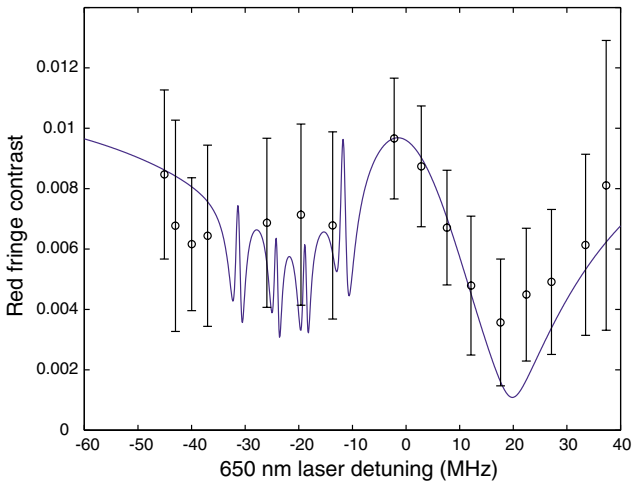

FIG. 3 (color online). Red fringe contrast vs detuning of the 650 nm laser for the data set of Fig. 2. The curve is calculated from Bloch equations with an effective solid angle of $\varepsilon = 1.6\%$ of 4π. The error bars are due to shot-to-shot variations. The maximum observed contrast of a single shot corresponds to $\varepsilon = 3\%$.

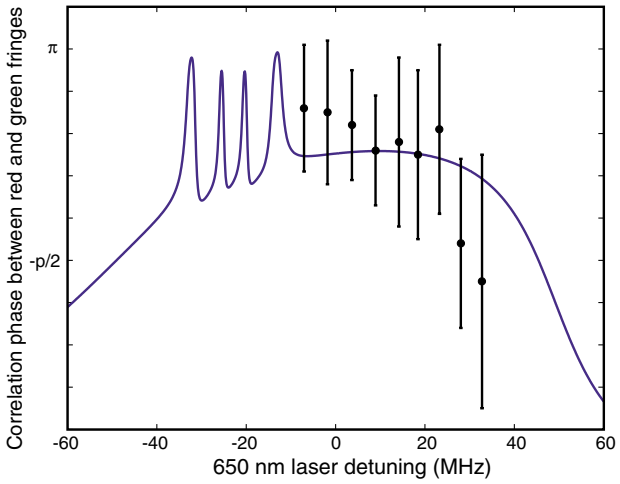

FIG. 4 (color online). Measurement of correlation phase vs red detuning in a case when for large positive detunings the correlation phase goes back to zero rather than reaching 2π. Because of suboptimal laser cooling, resulting from high red laser power, the fringe contrast goes down, which leads to the large error bars.

In summary, we have experimentally verified that a distant mirror shifts the energy of the excited atomic levels by modifying the electromagnetic vacuum around an atom and the atom's radiation reaction. While for nonlocalized atoms traversing resonators this effect has been observed earlier, in our case only a single mirror is used, and the spatial dependence of the energy shift is exploited by using a single trapped ion whose position is controlled on the subwavelength scale. Because of the multilevel structure of the ion, further effects arise which distinctly deviate from the behavior of simpler systems. While our experiment is designed to produce large level shifts, in the range of a few 100 kHz, already much smaller values, which may accidentally appear due to nearby dielectric objects, would be relevant in precision measurements or optical clocks with single atoms.

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