SINGLE IONS INTERFERING WITH THEIR MIRROR IMAGES

JÜRGEN ESCHNER, CHRISTOPH RAAB, PAVEL BOUCHEV,
FERDINAND SCHMIDT-KALER, RAINER BLATT

Universität Innsbruck, Institut für Experimentalphysik,
Technikerstr. 25, 6020 Innsbruck, AUSTRIA
E-mail: Juergen.Eschner@uibk.ac.at

The spontaneous emission of an atom is inhibited and enhanced when the atom is placed into a structured dielectric environment [1]. When another atom of the same kind is nearby, their spontaneous emission may exhibit cooperative sub- and superradiance [2]. We study these most fundamental quantum optical processes by recording single photons emitted by a single trapped atom which interacts with its mirror image over a distance of 50 cm: By retroreflecting the fluorescence of a single trapped Ba^+ ion with a high-quality lens and a mirror 25 cm away, we observe interference fringes with 72% visibility as the mirror distance varies. Simultaneous observation of the light transmitted through the mirror shows the population of the upper level to vary in anticorrelation with the interference fringes, which indicates inhibition and enhancement of a single atom's single spontaneous emission events. When two ions are trapped, they interfere with each other's mirror images, which indicates super- and subradiance mediated by the distant mirror. In this case the fringe visibility is 5%. The experiment allows to study variations in the vacuum fluctuations around a trapped ion on a sub-optical scale and to determine its position with respect to the mirror with nanometer-resolution.

1 Introduction

Since the first single ion was experimentally prepared and observed [3], single trapped atoms have found numerous applications in various areas. These range from precision measurements of physical constants and frequency standards [4], over experiments on fundamental quantum mechanics, to their application for the storage and processing of quantum information.

The lasting interest in single trapped ions is based on two main experimental features which become possible through the combination of an ion trap, in particular of the Paul type, with laser cooling. Together these techniques result in a localization of the single particle to typically a few ten nanometers or even below, in temperatures in the sub-millikelvin regime, in a high degree of isolation of the ion from its environment, and in quasi unlimited interaction time.

During the last few years experiments with single atoms have moved on towards the coherent manipulation of their internal and motional quantum state. These prospects have opened another rich field of applications of single trapped atoms because such manipulations, when applied to several ions in the same trap, form the basis of one of the promising implementations of quantum information processing. Indeed, the preparation of pure quantum states [5,6], their unitary rotation with high fidelity [6,7], conditional dynamics [7], as well as deterministic entanglement of a trapped ion string [8] have already been demonstrated.

The results reported in this paper belong to the field of fundamental studies with single trapped particles which earlier have revealed such prominent effects as quantum jumps [9] and antibunching [10]. In the experiments described here, we investigate interference of the light emitted by single Barium ions in a Paul trap. In an initial study, we send spontaneously emitted photons through a Mach-Zehnder interferometer and observe interference fringes with high contrast. In the second experiment which is the main topic of this report [11], one or two ions are trapped and, by a special optical arrangement, their light is retroreflected and focused back on the ion(s). We show that this light not only exhibits interference but also acts back on the ion or, in the case of two ions, creates a coupling between them. The analysis of the experimental observations with simple model considerations shows that the fundamental effects behind the observations are, in the one-ion case, inhibition and enhancement of spontaneous emission due to a modification of the electromagnetic mode structure and, in the two-ion case, sub- and superradiant emission due to reabsorption of photons emitted by the other ion. While modified spontaneous emission has been observed in several experimental [12] systems and sub- and superradiant emission has been studied with trapped ions [13], our experiments together with their model description highlight in particular the intimate relation between these fundamental phenomena.

2 Experimental setup

A single Ba^+ ion is trapped in a Paul trap of 1.4 mm diameter; its oscillation frequencies ω_z (ω_r) in the trap potential are between 1.2 and 2 (0.6 and 1) MHz. The ion is laser-cooled by continuous excitation on its $S_{1/2} \leftrightarrow P_{1/2}$ and $P_{1/2} \leftrightarrow D_{3/2}$ resonance lines at 493.4 nm and 649.7 nm, respectively. See Fig. 1 for a schematic of the experiment and the relevant levels of Ba^+; more details are described in earlier publications [14]. Both lasers have linewidths well below 100 kHz. The laser beams are combined on a dichroic beamsplitter before they are focused into the trap, and both light fields are linearly polarized. The laser intensities at the position of the ion are set roughly to saturation. The 650 nm laser is tuned close to resonance, the 493 nm laser is red-detuned by about the transition linewidth (Γ = 15.1 MHz) for Doppler cooling. A 2.8 Gauss magnetic field which is orthogonal to both the laser wave vector and the laser polarization defines a quantization axis and lifts the degeneracy of the Zeeman sublevels. The precise parameters are determined by fitting an 8-level Bloch equation calculation to a scan of the fluorescence intensity vs. the detuning of the 650 nm laser [15], see Fig. 2 for an example. A high-quality lens (L1), oriented at 90° to the excitation beams and situated 12.5 mm away from the ion, collects the fluorescence light of the ion in 4% solid angle and transforms it into a parallel beam of 21.4 mm diameter.

In the initial experiment, this light is analysed with a Mach-Zehnder interferometer as sketched in Fig. 1b. In the main experiment displayed in Fig. 1a, a mirror 25 cm away retroreflects the 493 nm part of the light collimated with L1, while transmitting the 650 nm part. The mirror is angle-tuned for 180° back-reflection with a precision mirror mount and, for fine adjustment, with two piezo translators (PZTs). The retroreflected light is focused by L1 to the position of the ion and, together with the light emitted directly into that direction, it is collected with a second lens (L2) at -90° to the excitation beams and recorded with a photomultiplier (PM1). Coarse alignment, i.e. superposition of the ion and its mirror image, is controlled visually through L2 while fine adjustment is done by optimizing the signal. The distance between mirror and ion is varied by an amount d (in the range of ±1 μm) by shifting the mirror along the optical axis with another PZT. The 650 nm light transmitted through the mirror is recorded by a second photomultiplier PM2.

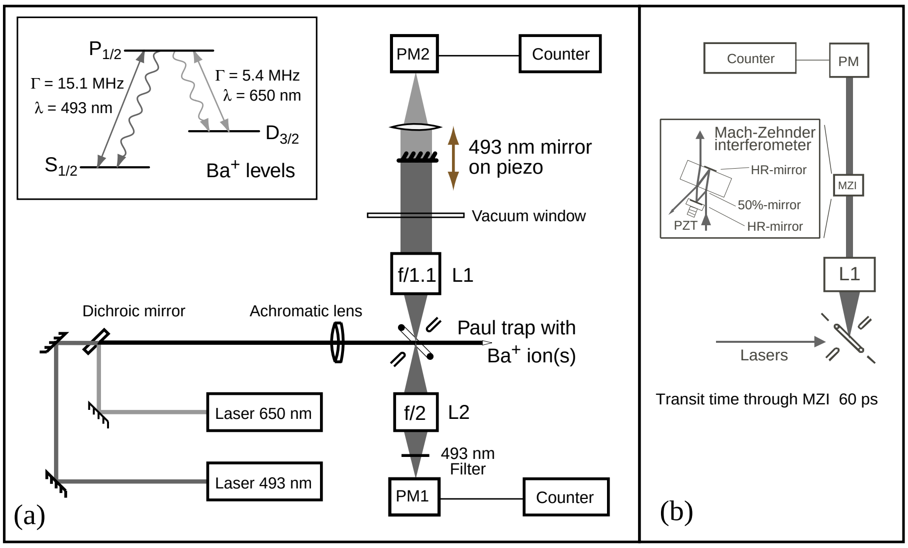


Figure 1. (a) Setup of the backreflection experiment and level diagram for Ba^+. See text for details. (b) Setup of Mach-Zehnder experiment.

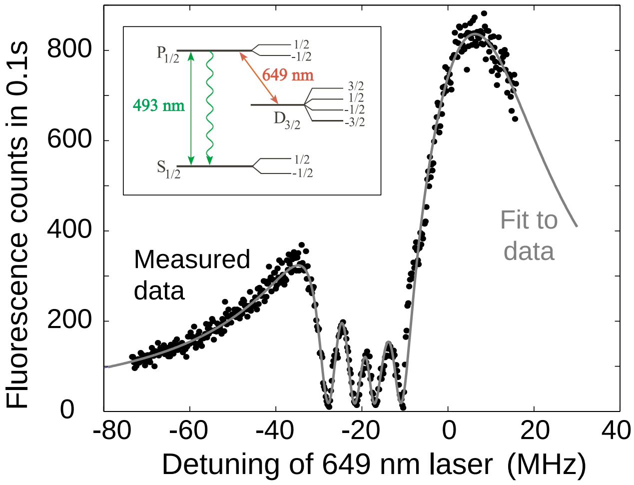


Figure 2. Inset: Levels of Ba^{+} with Zeeman structure indicated. Onset: Measured excitation spectrum (points), i.e. fluorescence counts vs. detuning of 650 nm laser, and fit calculated from 8-level optical Bloch equations (line). With the geometry used (quantization axis, laser beam, and polarization mutually orthogonal), four dark resonances are observed when the lasers excite a Raman resonance between an $S_{1/2}$ substate and a $D_{3/2}$ substate.

3 Results

3.1 Mach-Zehnder interferometer

When the light emitted by the single ion and collimated by L1 is sent through the Mach-Zehnder interferometer before its photons are counted, we observe interference fringes in the count rate as the interferometer is scanned. As shown in Fig. 3, the fringe visibility is close to 60%.

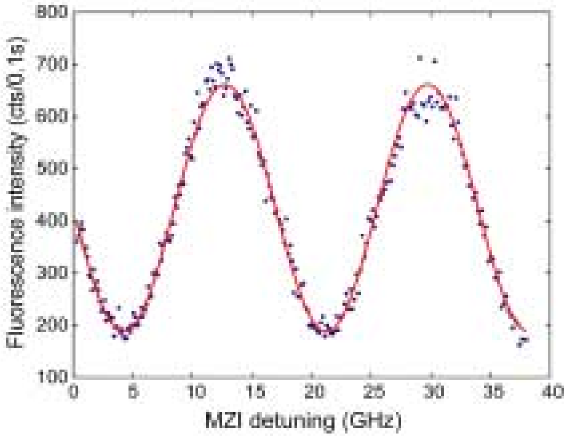


Figure 3. Photon count rate behind the Mach-Zehnder interferometer (MZI), as a function of the path length difference (or detuning). With 60 ps transit time through the MZI, a detuning of 16.7 GHz corresponds to a path length difference of $\lambda = 493$ nm.

It is instructive to look at the number of photons inside the interferometer: Its path length corresponds to a transit time of 60 ps, such that at the maximum count rate of $4.6 \cdot 10^3\ s^{-1}$ and with ~ 20% counting efficiency, the average number is $\sim 1.4 \cdot 10^{-6}$. The probability for two photons to be in the interferometer simultaneously is correspondingly smaller and it is even further reduced, by a factor $2 \cdot 10^{-3}$, due to the antibunching property of the single ion's resonance fluorescence. Therefore the interference fringes clearly demonstrate that every single photon interferes with itself, and the experiment combines nicely the wave and the particle character of the ion's resonance fluorescence.

3.2 Backreflection experiment with one ion

In this experiment, as displayed in Fig. 1a, a direct and a retroreflected part of the resonance fluorescence of a single Ba^+ ion are recorded together on PM1 while the distance between mirror and ion is varied. A scan of fluorescence vs. mirror shift is shown in Fig. 4. Interference fringes appear which repeat when the mirror is shifted by half the 493 nm wavelength. The interference contrast (or visibility V) in this example is 72%. We have identified various sources of visibility reduction: Residual thermal motion of the ion limits it to 93%, spectral broadening due to inelastic scattering reduces it by another 2%. The remaining reduction is caused by acoustic noise and abberations in the optical system.

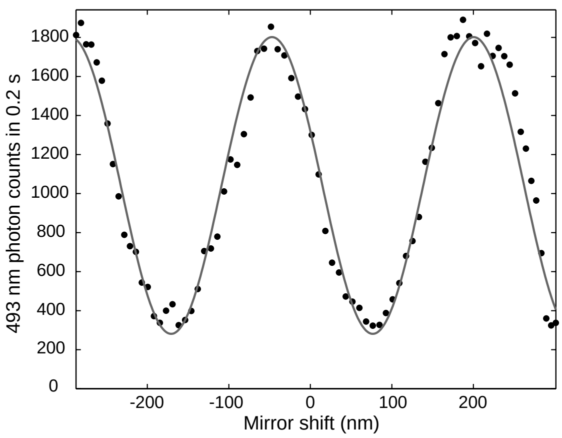
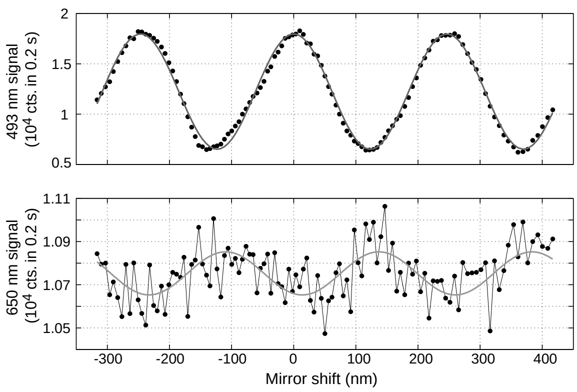


Figure 4. Interference of direct and back-reflected parts of the fluorescence of a single ion: Photon count rate at PM1 vs. mirror displacement (points). The fit (line) accounts for the nonlinear expansion of the PZT with applied voltage.

The observation shows clearly that light from the ion and from its mirror image, i.e. light scattered by the same atom into opposite directions, is coherent and can therefore interfere. While such interference would also be observed if the two light fields were superimposed on a beam splitter, the particular feature of this experiment is that the two fields are superimposed *at the position of the ion*. Thereby, our retroreflecting lens-mirror setup creates a *back-action* on the atom which is a fundamentally different effect. In an intuitive picture this back-action is explained by a modification of the electromagnetic vacuum at the position of the ion: The mirror creates nodes and antinodes in those modes which are collimated by the lens and then retroreflected, among them the modes which are analyzed by the detector. Since the spontaneous emission into any of these modes is proportional to the mode intensity at the position of the ion, we observe reduced or increased fluorescence depending on whether the ion is at a node or antinode, i.e. depending on its distance from the mirror.

If some fraction of the total fluorescence is suppressed or enhanced, we also expect the total rate of fluorescence to vary at roughly the same percentage level. An observation of such a variation would verify that a back-action takes place. Therefore we recorded, simultaneously with the interference fringes, the fluorescence at 650 nm which is transmitted through the mirror (see Fig. 1a) and which is directly proportional to the population of the excited $P_{1/2}$ level of the ion. The result is shown in Fig. 5. The 650 nm fluorescence exhibits a clear ~ 1% sinusoidal variation anticorrelated with the interference signal, indicating that an interference minimum (maximum) at 493 nm leads to higher (lower) population of the excited state. This shows that the mirror 25 cm away in fact acts on the internal atomic dynamics of the ion.

Figure 5. Interference fringes at 493 nm (top) and simultaneously recorded fluorescence at 650 nm transmitted through the mirror (bottom). Points are experimental data, bold lines are fits showing sinusoidal oscillations at the same frequency. The visibility of the modulation is 47% (top) and 0.9% (bottom). Within the experimental error the relative phase of the fits is in agreement with anticorrelation.



3.3 Backreflection experiment with two ions

With the same setup as before but with *two* laser-cooled ions in the trap, we adjust the mirror such that the mirror image of each ion is superimposed with the real image of *the other* ion. When we scan the mirror we find a result as displayed in Fig. 6. Again, interference fringes appear with the same period as before and with about 5% contrast. However, their interpretation must be clearly different since it is not light from the same atom that interferes, neither is there a back-action of an atom on itself. Instead, the two indistinguishable processes which create the interference are emission by one ion towards the detector and emission by the other towards the mirror, and the two atoms interact *with each other*.

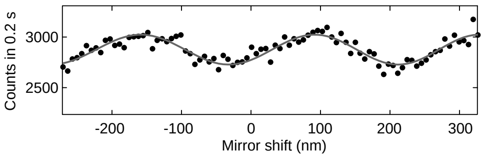


Figure 6. Interference fringes as in Fig. 4 but now with *two* ions, each interfering with the mirror image of the other. The visibility is ~ 5%; the main reason for its reduction, compared to the one-ion experiment, is the strong driven (micro-) motion of the ions in the Paul trap when their mutual repulsion displaces them from the trap center.

4 Model description

To include the back-action (or interaction) created by the mirror into the description of the system we have to take into account that when a photon reaches the detector, the two directions into which it can have been emitted are indistinguishable. This is represented in the Optical Bloch Equations (OBEs) for the atomic dynamics by adding coherently the two decay processes, one of them delayed by the travel time τ to the mirror and back [11].

A corresponding model calculation for the one-ion case, using the parameters of Fig. 5, indeed predicts a variation of the total fluorescence with the ion-mirror distance by 0.9% when the effective fraction of the total emitted light which can be brought to interference is set to 1.7%. Such a variation of the total fluorescence rate due to mirrors or other dielectric boundary conditions is usually called inhibited and enhanced spontaneous emission; it can also be regarded to result from reabsorption or stimulated emission induced by the back-reflected photons.

In the 2-ion case, the two indistinguishable processes which interfere are emission by one ion towards the detector and emission by the other ion towards the mirror. Using the same tools as for a single ion, we now modify the OBEs for the 2-atom density matrix correspondingly, finding that a new term appears in the dynamics which describes simultaneous emission by one ion and absorption by the other and which is modulated with the distance between the ions via the mirror. This shows that in fact reabsorption (and its inhibition) of the emitted photons goes along with the observed interference in the two-ion case. A slightly different viewpoint is that, depending on the delay τ, either the symmetric or the antisymmetric two-atom wave function is preferentially populated, which leads to enhanced or suppressed collective spontaneous emission, respectively. This is sub- and superradiance as originally described by Dicke [2].

In an earlier experiment [13] the corresponding lifetime modification was studied with two ions whose spacing was reduced to about 1.5 μm by a strongly confining trap. In our case, their interaction is mediated by the lens-mirror system over a distance of 50 cm.

5 Discussion

Apart from its fundamental aspects, the experiment has some interesting practical implications: We can regard the setup as a microscope to determine the position of the ion relative to the mirror, the precision of such a measurement being limited only by the noise in the photon counting signal. With the parameters of Fig. 4, we find that the Poissonian counting error translates into an error of the position measurement of only 1.7 nm. This means that within a typical measurement time of 0.1 to 1 s the center position of the ion can be determined more precisely than the extension of its ground state wave packet in the trap (~ 7 nm), which opens up exciting possibilities of measuring and even manipulating the position and motion of the ion on a scale below its position uncertainty. In the same sense our interference signal reveals spatial variations in the electromagnetic mode structure around the ion on a sub-optical scale; here the resolution is set by the thermal wave packet (~ 35 nm). A related study, using a Ca^+ ion in an optical resonator, has been presented in another contribution to this conference [16].

We have also observed that the interference signal can be used as a very sensitive detector for the driven (micro-) motion of the ion in the Paul trap. In turn, observation of that motion reveals more details of the electromagnetic mode structure around the ion. This will be the scope of future studies.

In summary, we have used a retroreflecting mirror at a distance of 25 cm to suppress or enhance the spontaneous emission events of a single trapped atom into the retroreflected modes by up to 72%. The total spontaneous emission rate is modified by ~ 1%. When two atoms are trapped, their spontaneous decay can be correlated via the mirror to produce sub- and superradiant emission. The experiments highlight the intimate relation between these fundamental quantum optical one- and two-atom effects. They are also very encouraging in the view of currently ongoing efforts to couple one or two single atom(s) to the mode of a high-finesse cavity, which is an important step in experimental quantum information processing.

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