INTERFERENCE IN THE RESONANCE FLUORESCENCE OF TWO TRAPPED ATOMS *

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ABSTRACT

We report the observation of interference in the resonance fluorescence of two localized atoms irradiated by laser light. The fringe visibility can be explained in terms of X-ray scattering by a harmonic crystal and by simple "which-path" arguments for the scattered photons. Polarization-sensitive detection of the resonance fluorescence demonstrates complementarity without invoking the position-momentum uncertainty relation.

INTRODUCTION

Light scattering from two atoms fixed in space was described theoretically by Heitler as early as 1954.[1] He obtained a simple interference formula for the scattered light using perturbation theory. The light scattering off the two atoms can be viewed as Young's double slit interference experiment with the slits replaced by the atoms. With the advent of trapping and laser-cooling of single atoms, the realization of such an interference experiment has become feasible.[2] The key point is to localize each of the two atoms within less than the wavelength of the scattered light.

Refined two-slit experiments attract increasing interest in the context of the problems of the early days of quantum mechanics, namely, the complementarity of waves and particles.[2,3,4] The concept of complementarity, which prohibits a simultaneous observation of wave and particle behavior, is often discussed in form of *gedanken*-experiments. The position-momentum uncertainty relation is usually recalled to enforce complementarity. Once the "which-path" information is obtained, the wave character is destroyed and interference is no longer detectable.

The experiment described in the following offers a way to turn the *gedanken*-experiments into reality. By exploiting the internal structure of the atom, we can obtain the "which-path" information to show complementarity without invoking the position-momentum uncertainty relation. By observing the scattered light in a polarization-sensitive way, we can select either the particle or the wave character of the scattered photons.

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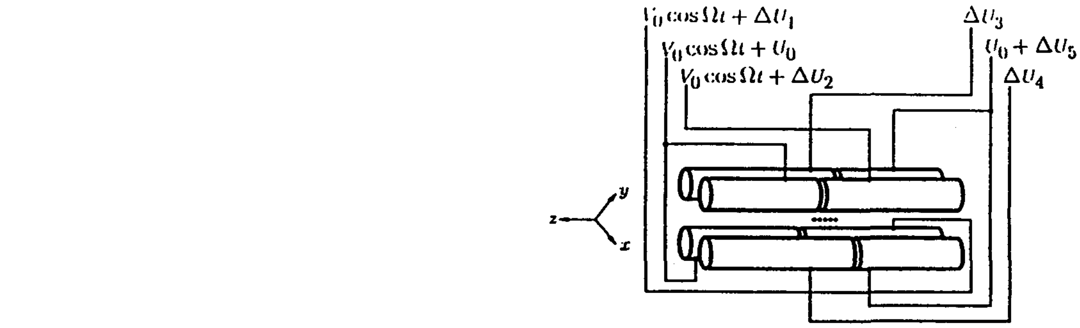

Figure 1: Linear rf trap. A rf voltage $V_o \cos(\Omega t)$ is applied to the four segments of two opposing trap rods. The two other rods are kept at rf ground. The voltages ΔU_1 to ΔU_5 allow for compensation of stray and patch fields. The diameter of the trap rods is 1.59 mm. See text for further explanation.

APPARATUS

We first start out with a brief description of the linear rf trap, which has been described in detail elsewhere.[5] Because of its geometry, the linear rf trap is particularly well suited for the interference experiment. Along the trap axis there is a nodal line for the rf drive field which minimizes the micromotion of ions confined along the axis. A strong localization of two ions in the trap is therefore possible. The trap consists of four trap rods each divided into two segments of unequal length (Figure 1). Trapping of the ions in the radial direction (x and y directions) was accomplished by a rf potential $V_o \cos(\Omega t)$ applied to the four segments of two opposing trap rods. The 1.2 kV amplitude of the 7.77 MHz rf drive was generated by a helical resonator, which acted as a resonant transformer. A static voltage U_o applied to the shorter segment of all four rods provided confinement in the axial (z) direction. Additionally, voltages ΔU_1 to ΔU_5 allow for compensation of stray and patch fields as well as correcting geometrical trap asymmetries.

Isotopically pure neutral ^{198}Hg was ionized in the trap by electron impact. The even isotope allowed simple laser cooling without optical pumping effects. The ions were cooled by radiation from a linearly polarized laser beam tuned below the resonance frequency of the $^{198}\text{Hg}^+$ $6s\ ^2S_{1/2} - 6p\ ^2P_{1/2}$ transition at 194 nm. The low temperatures (about 2 mK at the Doppler cooling limit) permitted strong localization of the ions in the trap. The laser beam waist was about 50 μm, and the laser power could be varied to a maximum of 50 μW.

The scattered light from the ions (resonance fluorescence) was observed with two position-sensitive imaging detectors D_1 and D_2 (Figure 2). On one side, a lens system produced a real image of the ion crystals on detector D_1. This allowed for a continous monitoring of the number of trapped ions. Detector D_2 was set to

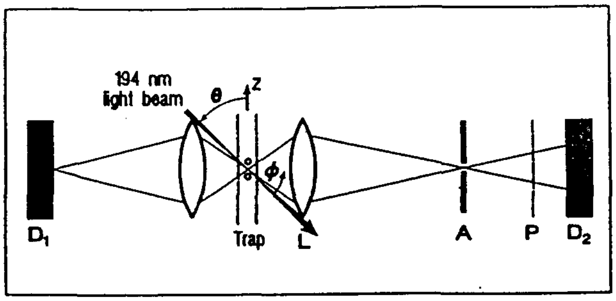

Figure 2: Schematic diagram of the experiment (see text for explanation).

measure the intensity of the scattered light as a function of the scattering angle. An $f/1$ lens collected the scattered light and imaged it with a magnification of 4.7 onto the aperture A, 300 μm in diameter. The light was then directed to the position-sensitive detector D_2, 0.1 m from the aperture. The polarizer P could be inserted to enable polarization-sensitive detection of the scattered light.[2] The ion spacing adjusted by the axial voltage U_o ranged from 9 μm to 3.3 μm. The spacings were calculated using the single-ion axial secular frequencies, which were measured as a function of the applied voltage U_o.

INTERFERENCE EXPERIMENT

In the interference experiment the cooling laser beam served two functions. It acted as the cooling laser and as the coherent light source. The beam was directed through the center of the trap at an angle $\theta = 62°$ with respect to the trap's z-axis (Figure 2). The detector D_2 covered an in-plane detection angle $\phi = 10°$ to 45° with respect to the beam direction. The fringe contrast is expected to be high for these detection angles. Figure 3 shows two interference patterns measured without the polarizer P at ion spacings a) $d = 3.9$ μm and b) $d = 3.4$ μm. As expected, the fringe spacing decreases with increasing ion separation. Furthermore, the fringe visibility diminishes with increasing scattering angle, indicating the loss of coherence due to the residual ion motion. For two atoms fixed in space as calculated by Heitler[1] the fringe contrast is 100 percent, independent of the observation angle. The larger the spacing between the two ions is, the weaker is the confinement for each ion in the z direction. For maximum spacing, axial confinement was only about 300 nm. Nevertheless, fringes could still be observed close to the laser beam direction. The rf amplitude was kept constant during the experiment providing radial confinement of about 30 nm.

The fringe contrast and spacing can be calculated using the formalism of X-ray scattering from a harmonic crystal.[2,6] The scattered light intensity as a function of momentum transfer $\hbar\vec{q} = \hbar(\vec{k}_{\rm out} - \vec{k}_{\rm in})$ can be expressed as[2]

$$I(\vec{q}) = 2I_o\left(1 + \cos(q_z d)\exp\{-\langle[\vec{q}\cdot(\vec{u}_1 - \vec{u}_2)]^2\rangle/2\}\right), \qquad (1)$$

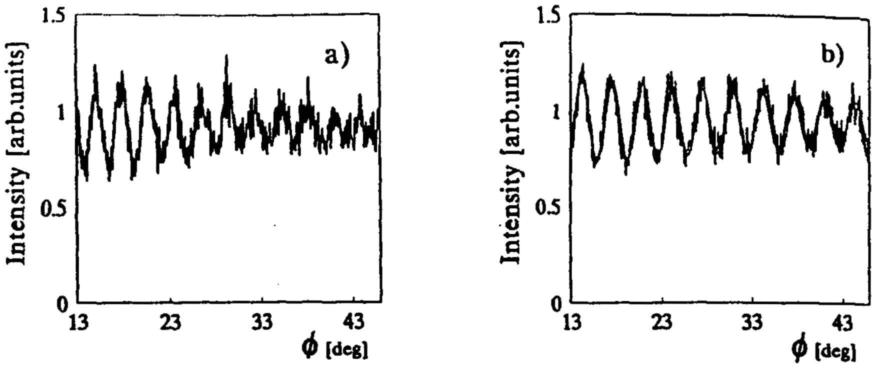

Figure 3: Shown are the interference fringes for a) d=3.9 μm and b) d=3.4 μm. Also shown in b) is a fit to the data (smooth line). From the fit we determined the temperature of the ions to be 1.5 times higher than the temperature at the Doppler cooling limit.

where $\vec{k}_{\text{out}}$ and $\vec{k}_{\text{in}}$ are the scattered and incident photon wave vectors and I_o represents the scattered intensity of a single ion (assumed to be equal for both ions). The brackets $\langle\rangle$ denote an ensemble average, and $\vec{u}_i$ denotes the displacement of the ith ion from its equilibrium position. We assume that the positions of the ions are characterized by a thermal distribution of the normal modes of the two ions in the trap. These modes are the stretch mode along the trap axis, two rocking or tilt modes normal to the trap axis, and the center-of-mass modes. The center-of-mass modes, however, are absent from the exponential factor in Eq. (1). These modes do not contribute to loss of fringe contrast, because they do not affect the relative phase of the scattered light. The displacement vectors can be calculated from the residual kinetic energy in the normal modes, which depends on the cooling laser beam angle and on the natural linewidth of the transition.

To compare our data with theory, we normalized the interference data with respect to the detected fluorescence light of a single ion, which compensates for net efficiency variations across the detector. To fit Eq. (1) to the data we included a constant background intensity I_b. This background intensity I_b is partly due to stray light, partly due to incoherent fluorescence radiation (see below), and partly due to quantum jumps from the $6p\ ^2P_{1/2}$ state into the metastable level $5d^96s^2\ ^2D_{3/2}$, which leave only one ion fluorescing. As the result of the fitting procedure, we found excellent agreement for all measured interference patterns with a temperature of about twice the Doppler cooling limit. Since the laser detuning and the degree of saturation were not precisely determined, these slightly higher temperatures were expected. Figure 3b shows as an example a fit to the data taken for an ion separation $d = 3.4\ \mu$m. The fitting results suggest that interference patterns can serve to determine ion temperatures and relative positions of two ions in a trap.

In order to elucidate Eq. (1) a little further, a comparison with the large crystal case seems to be appropriate. First, our detector does not differentiate between elastically and inelastically scattered light. Both processes contribute to the detected interference signal, which has been considered in Eq.(1). Inelastic scattering occurs when the normal modes of the two ions are excited. This is analogous to phonon excitation in X-ray scattering by crystals. The zero phonon order in crystals corresponds to the elastically scattered light and gives rise to sharp peaks at angles which satisfy the Bragg condition. However, in the two ion case, if we could measure the elastic scattering separately, the sharp peaks would be replaced by a smooth $1+\cos(q_z d)$ function due to the limited number of atoms in our "ion crystal". The fringe contrast would be 100 percent independent of the detection angle. In contrast to the case of two atoms fixed in space the intensity would be weighted by an overall exponential factor (the Debye-Waller factor) as it is in the case of elastic X-ray scattering by crystals. The loss of fringe contrast expressed by the exponential factor in Eq. (1) stems from all inelastic scattering processes, that is, all phonon orders.

"WHICH-PATH" EXPERIMENT

In discussions of Young's-type interference experiments, the position-momentum uncertainty relation is often used to show that it is impossible to determine through which slit the photon or particle passes without interacting with the photon or particle strongly enough to destroy the interference pattern. But the position-momentum uncertainty relation need not be invoked. The present experiment offers the possibility to obtain "which-path" information by exploiting the internal level structure of the atom. The $^{198}Hg^+$ ground state $6s\ ^2S_{1/2}$ and the excited state $6p\ ^2P_{1/2}$ are twofold degenerate with respect to the magnetic quantum number m_J. The effect of this level structure is that scattering linearly polarized light off the two ions can result either in π- or σ-polarized scattered light. Assume that only one photon is scattered at a time. In the case of π-polarized scattered light ($\Delta m_J = 0$) the ions' final states are the same as the initial states. Which atom scattered the photon cannot be determined. Quantum mechanics therefore predicts that interference must be present in the light scattered from the two ions. On the other hand, observation of the σ-polarized scattered light ($|\Delta m_J| = 1$) indicates that the final state of one atom differs from its initial state. This allows us, at least in principle, to distinguish the scattering atom from the "spectator" atom, and hence to determine which path the photon traveled. Consequently, there is no interference in the light scattered from the ions. Thus, polarization-sensitive detection of the scattered photons can serve as a switch to extract either the wave-like or the particle-like character of the scattered photon.

Figure 4 shows the results (unnormalized) of the polarization-sensitive detection. Figure 4a displays the interference pattern as expected for the case of π-scattered light. When σ-scattered light was detected, no interference pattern could be observed (Fig. 4b), in agreement with the quantum mechanical predictions.

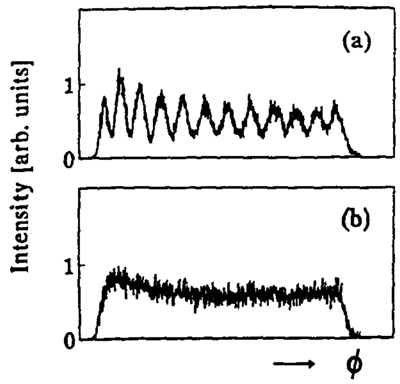

Figure 4: Polarization-sensitive detection of the scattered light (unnormalized): (a) π-polarized scattered light, showing interference, (b) σ-polarized scattered light, showing no interference (see text for explanation)

CONCLUSION

We observed interference in the light scattered from two localized atoms. The measured fringe pattern and contrast can be explained in the framework of X-ray scattering by a harmonic crystal. The results show that interference measurements provide another method to determine ion temperatures and separations in traps. By exploiting the atom's internal level structure, we showed, without invoking the position-momentum uncertainty relation, that the possibility of determining the path of the scattered photon destroyed the interference fringes. Future plans aim at the investigation of saturation effects on the fringe contrast and at the observation of interferences in the scattered light from more than two ions. We have already observed interference in the scattering light from three ions.

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