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Young's Interference Experiment with Light Scattered from Two Atoms

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We report the first observation of interference effects in the light scattered from two trapped atoms. The visibility of the fringes can be explained in the framework of Bragg scattering by a harmonic crystal and simple "which path" considerations of the scattered photons. If the light scattered by the atoms is detected in a polarization-sensitive way, then it is possible to selectively demonstrate either the particle nature or the wave nature of the scattered light.

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Young's two-slit experiment [1], in the context of wave-particle duality, is often regarded as a paradigm for quantum phenomena. To some it "has in it the heart of quantum mechanics. In reality it contains the only mystery" [2]. In this Letter we report, for the first time, a version of Young's experiment where we detect the interference of weak laser light scattered from two localized atoms which act as two slits. The visibility of the interference fringes has a simple interpretation in terms of Bragg scattering and "which way" arguments based on the changes of the atoms' internal states.

Interference of light scattered from atoms has received recent attention because it has provided information on the degree of localization of laser-cooled neutral atoms in optical wells [3, 4]. Optical interference has also been observed in the time-resolved atomic fluorescence following the photodissociation of a molecule [5]. Although fixed numbers of atomic ions have been localized in ion traps [6–9], interference has not been previously reported due, in part, to inadequate localization. In the experiments described here, we observe interference of light scattered from two $^{198}Hg^{+}$ ions localized in a linear Paul trap [10].

The experiment is shown schematically in Fig. 1. Using established procedures, we trapped two $^{198}Hg^{+}$ ions along the axis of a linear trap [10]. The ions were irradiated by a linearly polarized, traveling wave laser beam tuned below the resonance frequency of the $^{198}Hg^{+}$ $6s\,^2S_{1/2}$–$6p\,^2P_{1/2}$ transition at 194 nm. The beam serves two functions in the experiment. It reduces the ions' kinetic energy by preferentially imparting photon momentum to them in a direction that opposes their motion (Doppler laser cooling) [11]. The low temperatures strongly localize the ions in our trap. The beam also

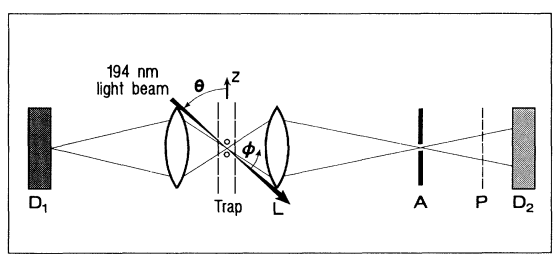

FIG. 1. Schematic diagram of the experiment. Scattered light from two ions (represented by small circles near the center of the trap) was imaged onto detector D_2 via the collecting lens L, aperture A, and an optional polarizer P. The polarizer was a UV-absorbing glass plate oriented at Brewster's angle (see text). Detector D_1 served as a monitor of ion number.

acts as the light source for the interference experiment. It was directed through the center of the trap at an angle θ=62° with respect to the trap axis (z axis). The beam waist was about 50 μm and the laser power could be varied to a maximum of about 50 μW. A 7.77 MHz rf drive with an amplitude $V_0 \simeq 1$ kV confined the ions radially while a static voltage U_0 applied to both ends of the trap provided axial confinement. Scattered light was observed with two position-sensitive imaging detectors D_1 and D_2 (Fig. 1). On one side, a lens system produced a real image of the ions on detector D_1 [10]. This allowed for continuous monitoring to make sure that exactly two ions had been trapped. On the opposite side, detector D_2 was set up to measure the intensity of the light as a function of the scattering angle. This scattered light was collected with an $f/1$ lens and imaged with a magnification of 4.7 onto an aperture 300 μm in diameter. The light that passed through the aperture was directed onto the position-sensitive photocathode of detector D_2 about 0.1 m from the aperture. Although the interference fringes could, in principle, be detected using D_2 alone, the lens and aperture suppressed background stray light from reaching the detector. With this configuration, detector D_2 covered an in-plane detection angle ϕ = 10° to 45°, where ϕ is defined with respect to the 194 nm beam direction and the plane is defined by the traps z axis and the 194 nm beam. The out-of-plane detection angle Φ ranged from −15° to 15°. The ion separation d could be adjusted by varying the axial voltage U_0. The separation can be calculated with our trap parameters using the formula $d = 19.4U_0^{-1/3}$, where d is in μm and U_0 is in volts [8]. In the experiment, U_0 was varied between 10 V and 200 V, which produced spacings from 9 μm to 3.3 μm, respectively. At these separations, the dipole-dipole interaction between ions can be neglected.

Figure 2 shows examples of the experimental results with polarization-insensitive detection. The fringes were recorded at three different ion separations: 5.4 μm, 4.3 μm, and 3.7 μm. The fringe spacing increases with decreasing ion separation, as expected. Additionally, the fringe contrast is highest close to the forward scattering direction and deterioriates with increasing ϕ. At higher angles ϕ, the scattered light loses its coherence due to the residual ion motion.

We have performed calculations that quantitatively describe the fringe contrast and spacing. These calculations proceed along the same lines as those for Bragg scattering by a harmonic crystal [12] and use Fermi's "golden rule" to determine the scattering rate from an initial state to a final state. Since our detector does not differentiate between elastically and inelastically scattered light, both processes contribute to the detected interference signal. We have calculated the loss of contrast caused by the residual ion velocity at our ion temperatures and find it to be negligible. Also, loss of fringe contrast due to the resulting variations in the energy of the scattered light is negligible. We obtain the scattered light intensity as a function of momentum transfer $\hbar\mathbf{q} = \hbar(\mathbf{k}_{\rm out} - \mathbf{k}_{\rm in})$:

$$I(\mathbf{q}) = 2I_0(1 + \cos(q_z d)\exp\{-\langle[\mathbf{q}\cdot(\mathbf{u}_1 - \mathbf{u}_2)]^2\rangle/2\}), \tag{1}$$

where $\mathbf{k}_{\rm out}$ and $\mathbf{k}_{\rm in}$ are the scattered and incident photon wave vectors and I_0 represents the scattered intensity of a single ion (assumed to be equal for both ions). The brackets $\langle\,\rangle$ denote an ensemble average and $\mathbf{u}_i$ 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. Excitation of these modes during the scattering process gives rise to inelastic light scattering similar to phonon excitation processes in Bragg scattering by crystals. If we could measure only the elastically scattered contribution, it would have 100% fringe contrast independent of the momentum transfer, but the intensity would be weighted by an overall exponential factor (the Debye-Waller factor) as it is in the case of elastic Bragg scattering by crystals. The fringe contrast expressed by the exponential factor in Eq. (1) is due to the contribution of inelastic scattering processes in the interference of light scattered from two atoms. For two ions with fixed posi-

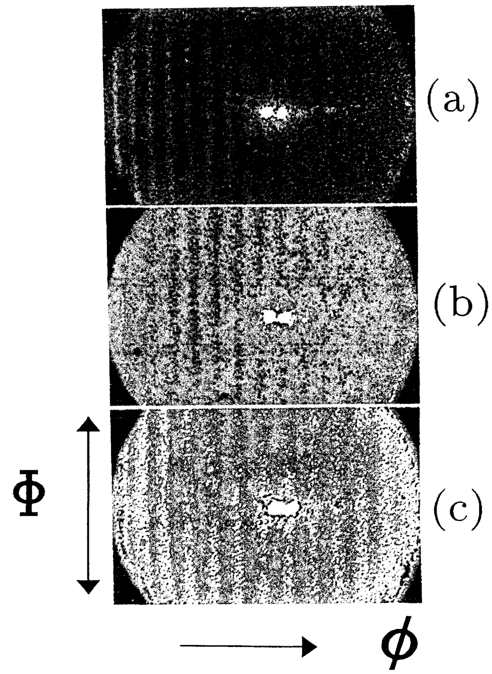

FIG. 2. Interference pattern for three different ion separations: (a) 5.4 μm, (b) 4.3 μm, and (c) 3.7 μm. The two white spots are caused by stray reflections of the laser beam.

tions, Eq. (1) recalls the result obtained by Heitler in his classic treatment of resonance fluorescence [13] giving a fringe contrast equal to 1. The center-of-mass modes are absent from the exponential factor. These modes do not contribute to loss of fringe contrast, because they do not affect the relative phase of the scattered light.

We can calculate $\langle[\mathbf{q}\cdot(\mathbf{u}_1-\mathbf{u}_2)]^2\rangle$ from the residual kinetic energy (temperature) in the normal modes of the two ions given by $k_B T_j/2 = m_j \omega_j^2 \langle X_j^2\rangle/2$, where k_B is the Boltzmann constant, j denotes the mode, m_j is the effective ion mass for mode j (for the stretch and tilt modes m_j equals one-half of the single ion mass), and $\langle X_j^2\rangle$ is the mean squared amplitude of the modes. At the Doppler-cooling limit, the kinetic energy of the stretch mode is $\{1+[3\cos^2(\theta)]^{-1}\}\hbar\gamma/8$ and the kinetic energy of the rocking mode is $\{1+[3\sin^2(\theta)]^{-1}\}\hbar\gamma/8$ [11], where γ is the natural linewidth. Since the laser detuning and the degree of saturation were not precisely determined, we might expect somewhat higher kinetic energies. The frequencies of the normal modes are conveniently expressed in terms of the single-ion secular frequencies, which can be easily measured. We have $\omega_{\text{stretch}} = \sqrt{3}\omega_z$ and $\omega_{\text{tilt}} = (\omega_r'^2 - \omega_z^2)^{1/2}$, where the single-ion axial and radial secular frequencies at the maximum applied voltages were about $\omega_z/2\pi$=1 MHz and $\omega_r'/2\pi$=1.5 MHz, respectively.

To compare our data with theory, we normalized the interference data with respect to the detected fluorescence light of a single ion. This method compensates for net efficiency variations across the detector. Furthermore, we need to include a constant background intensity I_b. This background 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 $5d^9 6s\ ^2D_{3/2}$ [14], which leave only one ion fluorescing. The background due to single-ion fluorescence caused by quantum jumps depends on the mean population of the $6p\ ^2P_{1/2}$ state and the lifetime of the metastable state.

We fitted Eq. (1) (including I_b) to the data and found excellent agreement for all measured interference patterns with a temperature of about twice the 1.7 mK Doppler-cooling limit. Radial confinement was about 30 nm, and the residual amplitude in the axial direction was about 60 nm to 300 nm, depending on U_0. Figure 3 shows an example where U_0=193 V, corresponding to an ion separation of 3.4 μm.

Our experiment resembles the classic Young's two-slit arrangement with the slits replaced by the two atoms. 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. The position-momentum uncertainty relation need not be invoked; the destruction of the interference can arise due to correlation between the mea-

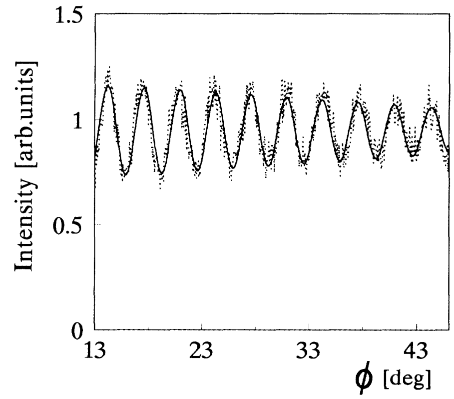

FIG. 3. Shown are the interference fringes for d=3.35 μm together with a fit to the data. For these data, the temperature of the ions was determined to be 1.5 times higher than the temperature at the Doppler-cooling limit.

surement apparatus and the measured system [15]. 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 in either π- or σ-polarized scattered light. Assume that only one photon is scattered at a time. In the case of π-polarized scattered light ($\Delta m_J = 0$ transition) 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 transition) 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. In this context, the existence of interference fringes indicates wavelike behavior, while the absence of fringes, consistent with a single photon trajectory, which begins at the source, intersects one of the atoms, and continues to the detector, indicates a particlelike behavior. Thus, polarization-sensitive detection of the scattered photons can serve as a switch to extract either the wavelike or the particlelike character of the scattered photon. These two complementary pictures are essentially classical. Both types of behavior are contained in the quantum description. The interference then occurs between Feynman path amplitudes, and the presence or absence of fringes depends on whether or not there are two or one possible paths from the initial state to the final state.

Our simple "which path" considerations are confirmed

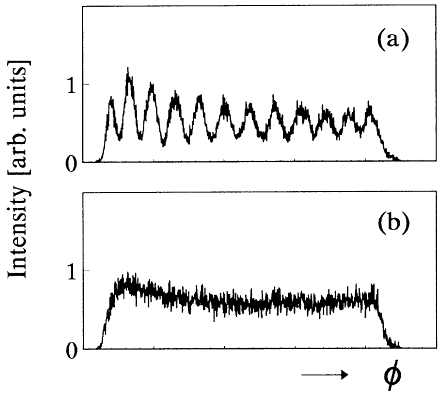

FIG. 4. Polarization-sensitive detection of the scattered light (unnormalized): (a) π-polarized scattered light, showing interference; (b) σ-polarized scattered light, showing no interference pattern as explained in the text.

by a detailed theoretical study of the coherence properties of the resonance fluorescence from a single atom with the same level structure as $^{198}Hg^+$ [16]. It reveals that for a weak, linearly polarized field, only the π-polarized scattered light is coherent, while the σ-polarized components are incoherent.

In our experiment, polarization-sensitive detection of the 194 nm scattered light was accomplished with a glass plate oriented at Brewster's angle. It was mounted between the aperture and the detector. Light linearly polarized normal to the plane of incidence of the Brewster plate was reflected toward the detector with about 15% efficiency. Light polarized in the plane of incidence was transmitted into the glass, where it was absorbed. Consequently, with the laser beam polarized normal to the plane of incidence, π-scattered light was detected. Conversely, when the laser beam was polarized in the plane of incidence, the π-scattered light was absorbed, and only σ-scattered light reached the detector. Figure 4 shows the results (unnormalized) of the polarization-sensitive detection. Figure 4(a) 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. 4(b)], in agreement with the quantum mechanical predictions.

In summary, we have reported the observation of interference fringes in the light scattered from two localized atoms driven by a weak laser field. The measured fringe pattern and contrast can be explained in the framework of Bragg scattering by a harmonic crystal. These 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 prospects include measurements of the dependence of the fringe contrast on the saturation of the atomic transition, since the coherent component decreases in a predictable way as the light field intensity is increased [17]. We plan to study the interference pattern of more than two ions and have already been able to observe the interference pattern of three ions. Finally, heterodyne measurements could distinguish the different contributions of the elastic and inelastic scattering processes to the interference pattern.

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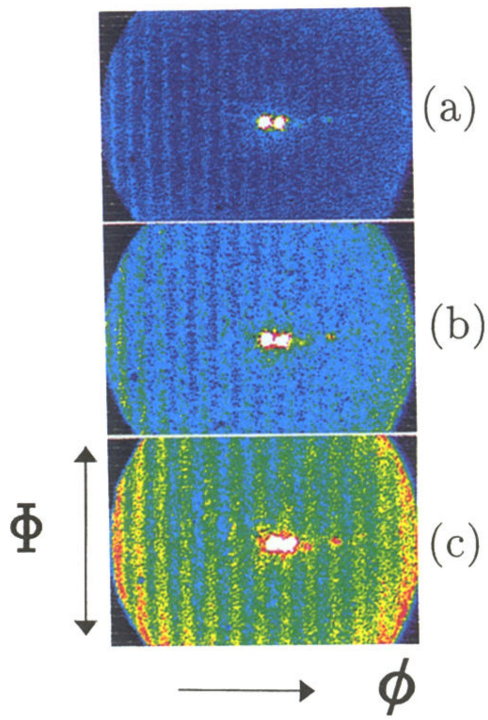

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