Towards high-fidelity interference of photons emitted by two remotely trapped ^{87}Rb atoms

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We investigate the requirements for achieving high-fidelity interference of photon pairs emitted by two independently trapped ^{87}Rb atoms at remote locations. For this purpose one has to ensure indistinguishability of the single photon wave packets. The crucial parameters here are the synchronization of the two setups, the frequency matching of the photons, as well as their spatial mode overlap. We show that in our experiment these parameters can be controlled to a high degree. This is a first step towards entangling two trapped atoms over a large distance.

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I. INTRODUCTION

Entanglement between remote atomic quantum memories is a key resource for future applications in quantum communication like the quantum repeater [1]. One possibility to generate entanglement between remote atomic systems is entanglement swapping [2]. This protocol consists of two steps. In the first step each memory device is entangled with a photonic carrier of quantum information. Then a Bell-state measurement is performed on the photonic carriers thereby projecting the atomic system onto a maximally entangled state.

When the polarization degree of freedom of single photons is used as the information carrier, the Bell-state measurement on two photons can be performed by interfering them on a 50-50 beam splitter [3, 4]. The Hong-Ou-Mandel effect [5] leads to bunching of indistinguishable photons, i.e. both particles leave the beam splitter from the same output port. It can be shown that for entangled input states only the antisymmetric state $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle - |V\rangle|H\rangle)$ does not bunch and can be therefore detected since the two photons go into different outputs of the beam splitter. A polarization analysis of the photons after interference additionally allows to detect the state $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle + |V\rangle|H\rangle)$ where two orthogonally polarized photons go into the same output port. It can be shown that this method is optimal for detecting Bell states with linear optics [6]. The feasibility of this scheme for separated atomic systems was demonstrated by observing quantum interference of photons emitted by two atomic ensembles [7] and by entangling two trapped ions [8] and atomic ensembles [9] over small distances. However in these experiments the atomic systems were not independent as they shared a common laser system and the separation was maximally few meters.

The goal of our current research is to entangle two single ^{87}Rb atoms which are stored in independent optical traps at remote locations separated by several hundred meters. The qubits are encoded into Zeeman sublevels of the $5^2S_{1/2}, F = 1$ hyperfine ground level. This system provides the necessary prerequisites for achieving entanglement over long distance. Previously we already demonstrated entanglement between the spin of the atom and polarization of a single, spontaneously emitted photon [10], as well as long coherence time of the involved atomic states [11], sufficient to implement the entanglement swapping protocol. In addition we have established an optical fiber link with active polarization stabilization [11] enabling long-distance distribution of atom-photon entanglement.

Here we describe the next step, where we connect the two atomic traps in order to observe quantum interference of single photons emitted by the atoms. The major building blocks of this experiment will be analyzed and estimates on achievable performance will be derived.

II. REQUIREMENTS FOR ACHIEVING HIGH-FIDELITY 2-PHOTON INTERFERENCE

In order to achieve a high fidelity Bell-state projection it is necessary to ensure that the contrast of interference is as high as possible [12]. Therefore the two interfering photons need to be indistinguishable in all degrees of freedom except polarization. This implies in particular:

- Temporal mode overlap: the photonic wave packets of identical shape need to arrive simultaneously. This requires exact synchronization of the two independent trap setups on a timescale much shorter than the coherence time of the emitted photons (26.2 ns).
- Spatial mode overlap: the matching of the spatial modes for both photons directly influences the interference contrast.
- Spectral mode overlap: the frequency distribution of the wave packets has to be identical. Here the external factors affecting atomic states like magnetic fields and light-shifts need to be considered, additionally the motional Doppler effect is important.

In the following we will consider the mentioned points in more detail.

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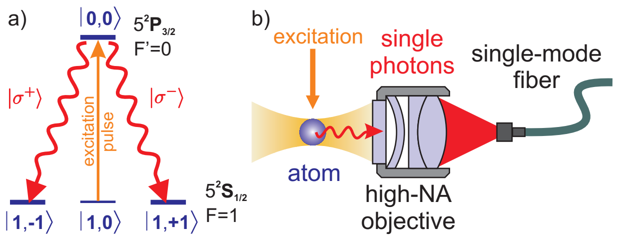

Figure 1: a) Principle of generation of single photons whose polarization is entangled with the atomic spin. b) The emitted photons are collected by an objective and coupled into a single-mode optical fiber for interference experiments.

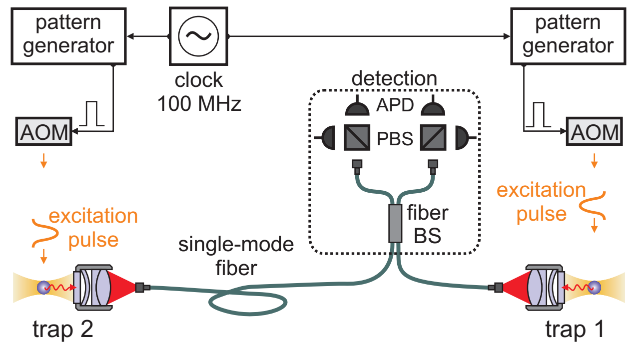

Figure 2: Two synchronized atomic traps located in separate laboratories. The optical excitation pulses are shaped by acousto-optic modulators (AOMs) such, that the emitted photons arrive simultaneously at the fiber beam splitter (BS) for interference. The timing is controlled by two electronic pattern generators driven by a common clock. The photons leaving the beam splitter are detected by avalanche photodetectors (APDs) after their polarization was analyzed by polarizing beam splitters (PBS).

III. SINGLE ATOM TRAPS AND GENERATION OF SINGLE PHOTONS

In our experiment single ^{87}Rb atoms are stored in two optical dipole trap setups [13] situated in neighboring laboratories 20 m apart. The traps are generated by focused Gaussian laser beams (waist $w_0 = 3.5\,\mu$m for the first trap and $w_0 = 1.9\,\mu$m for the second) at a wavelength of 856 nm. The trap depths are $U_0 = k_B \cdot 0.65$ mK and $U_0 = k_B \cdot 1.5$ mK, respectively. The loading is performed from laser-cooled clouds of $10^3..10^4$ atoms of shallow magneto-optical traps (MOTs). Typical trapping times in the dipole trap are about $5-10$ s.

The scheme for generation of atom-photon entanglement is shown in Fig. 1(a). It starts with $4.6\,\mu$s of optical pumping which prepares the atom in the initial state $5^2S_{1/2}$, $|F=1, m_F=0\rangle$. Then the atom is excited to the state $5^2P_{3/2}$, $|F'=0, m_{F'}=0\rangle$ by a short optical pulse (more details on optical pulses are given in Section IV). In the following spontaneous decay a single photon is emitted whose polarization is entangled with the atomic spin [10]. In order to maximize the photon generation rate, the pumping/excitation procedure is repeated 20 times, which takes $100\,\mu$s, after that laser cooling is applied for $200\,\mu$s to avoid atom loss out of the trap due to heating. This sequence achieves an excitation repetition rate of 66 kHz.

The light emitted by the trapped atoms is collected by high-NA objectives and coupled into single mode optical fibers, see Fig. 1(b). The collected photons can be detected either locally or guided to the other laboratory for interference experiments. The overall local detection efficiencies for single photons emitted by the atoms are $\eta_1 = 1.2 \cdot 10^{-3}$ and $\eta_2 = 1.8 \cdot 10^{-3}$ including the collection efficiency and quantum efficiency of the used single photon counting avalanche photo-detectors (APDs, Perkin-Elmer SPCM-AQR15).

IV. SYNCHRONIZATION OF TWO INDEPENDENT ATOMIC TRAP SETUPS

To maximize the temporal overlap of the interfering photons at the beam splitter the optical excitation processes of the two atoms have to be synchronized with high precision. As the two atomic traps operate independently, there is no common laser system and the excitation pulses are generated independently at the location of each atom. Hence the optimization of the temporal overlap requires exact timing. In more detail it implies also that the shape and the Rabi frequencies of the excitation pulses have to be matched.

The synchronization of the setups is achieved by using a common electronic clock generator, see Fig. 2. Its signal (100 MHz sine wave) drives two programmable electronic pattern generators [14] with a time resolution of 20 ns. The measured jitter between the two generators is $\sigma_{e\text{-}e} = 31$ ps RMS. The pulses provided by the generators are electronically shaped and fed into acousto-optic modulators (AOM) which shape the optical excitation pulses. This shape is approximately Gaussian with a FWHM of 23.5 ns and is identical for the two setups. The time jitter between the electronic and the optical pulses was measured in both setups with a fast photodiode giving $\sigma_{e\text{-}o} = 280$ ps. This results in a total jitter between the optical excitation pulses in the two traps of $\sigma_{o\text{-}o} = 400$ ps, far below the lifetime of the relevant excited atomic state.

The shapes of the single photon wave packets are measured by repeated excitation of the atoms and recording the arrival times of the photons. The histograms of arrival times are shown in Fig. 3. In order to achieve maximal overlap of the interfering single photons we have matched the intensities respectively the Rabi frequencies of the excitation pulses by comparing the steepness of the rising edges. The calculated overlap of the two wave packets in Fig. 3 is 0.989. Due to measurement noise this value represents only a lower bound on the real temporal overlap.

V. THE BEAM SPLITTER

In order to ensure perfect spatial mode overlap in the interference process, a single-mode fiber beam splitter is used. It is based on evanescent coupling between two single-mode fibers which are brought closely together. The length of the interaction region is tailored to achieve the desired cross-coupling, which in our case is 0.5. The relevant figures of merit of such a beam splitter are the splitting ratio and its polarization-dependence which directly affect the quality of interference.

The splitting ratios of the used device were characterized to be $T_H = 0.527$, $R_H = 0.473$, $T_V = 0.505$, $R_V = 0.495$, where T_H, R_H, T_V and R_V are polarization-dependent intensity transmission/reflection coefficients. One has to keep in mind that due to birefringence in the input and output fibers the polarization in the splitting region is in general unknown, even if the device is compensated such that the polarization between all inputs and outputs is preserved.

The method for Bell state measurement in our experiment is based on joint detections of orthogonally polarized single photons after interference on the beam splitter, heralding projection onto states $|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle \pm |V\rangle|H\rangle)$. A straightforward calculation shows that in the case of ideally indistinguishable photons the interference contrast is determined by the properties of the beam splitter as

$$Q_{BS} = \frac{2\sqrt{T_H T_V R_H R_V}}{R_H R_V + T_H T_V}. \quad (1)$$

With the values given above we arrive at $Q_{BS} = 0.998$. This imposes a limitation on the maximal achievable fidelity for a photonic Bell-state projection of

$$F_{max}^{BS} = \frac{1}{2}(1 + Q_{BS}) = 0.999.$$

VI. SPECTRAL CHARACTERISTICS OF THE EMITTED PHOTONS

The spontaneous atomic emission process is very favorable for interference experiments due to the well-defined frequency and long coherence length of the emitted photons. However, the atomic transition frequencies are subject to shifts by external electric/magnetic fields. Additionally, the thermal motion of the atom in the trap will lead to Doppler broadening and therefore the kinetic energy of the atom becomes an important parameter. In the following we will consider these effects in more detail.

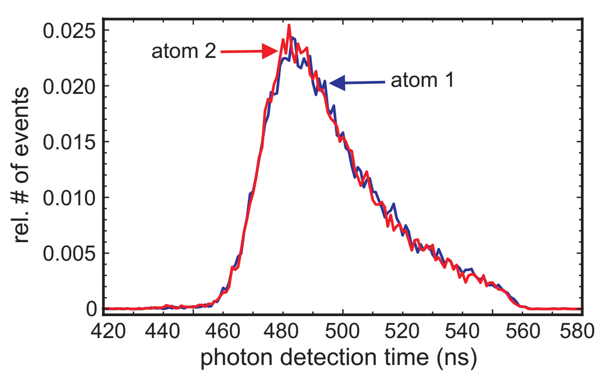

Figure 3: Histograms of the arrival time of single photons emitted by two optically trapped atoms after passing a fiber beam splitter. The arrival times were measured independently with respect to a common clock. Both histograms are individually normalized with respect to the total number of events.

A. Light-shifts

The working principle of the optical dipole trap is based on lowering of the atomic ground levels in the presence of an intense, far-detuned optical field. At the same time the energy of the excited states is typically raised, leading together to an overall variation of the frequency of the optical transition, the so-called light-shift. This shift is position-dependent and due to the thermal motion of the atom also time-dependent. It leads to an incoherent broadening of the emission spectrum and can thereby reduce the achievable interference contrast.

In order to eliminate the light-shifts in our experiment, the dipole traps are switched off during the excitation/emission processes for 140 ns. This time is on the order of 1% of the shortest oscillation period in the trap (16 μs), thus the reduction of the lifetime in the trap is very small. With this method the emission of the photon takes place in "free space" and is therefore not subject to light-shifts induced by the dipole trap.

B. Zeeman shifts

The second important contribution to the shifts of atomic transition frequencies is the Zeeman effect induced by external magnetic fields. The relevant ground states $|F = 1, m_F = \pm 1\rangle$, Fig. 1(a) experience a magnetic shift of $\pm 2\pi \cdot 0.7\,\mathrm{MHz/G}$, while the excited state $|F' = 0, m_F = 0\rangle$ is not subject to first-order Zeeman shift. Thus, in presence of a magnetic field the degeneracy of the ground states is lifted and the transition frequency of the two decay channels becomes different. This would have two consequences. First, the fidelity of the spin-polarization entanglement between the atom and the photon is reduced since the two decay channels become distinguishable. Second, the spectral distinguishability leads to a drop in the fidelity of the two-photon interference.

In our traps the magnetic fields are actively stabilized to values of $B < 10\,\mathrm{mG}$. For a worst-case estimation we assume that the field permanently takes its highest value of 10 mG. This corresponds to a shift of the Zeeman states of $\pm 2\pi \cdot 7\,\mathrm{kHz}$. The relative shift of corresponding Zeeman states between atoms in two traps is $2\pi \cdot 14\,\mathrm{kHz}$ in the extreme case of the fields being oriented in opposite directions. The reduction of the spectral overlap due to the latter frequency mismatch is of the order of $5 \cdot 10^{-6}$ as can be verified using (4). Thus, the Zeeman shift does neither degrade the fidelity of atom-photon entanglement nor the quality of two-photon interference.

C. Doppler shifts

Due to the finite temperature of the atoms they are subject to residual thermal motion. The component of this motion along the axis of the collection optics causes a first-order Doppler shift, while the transverse velocity components only lead to negligible higher-order (relativistic) shift. Therefore it is sufficient to consider only the velocity distribution for the axial degree of freedom of the atomic motion in the trap. Since the thermal energy of the atom is much lower than the trap depth, the trapping potential can be considered harmonic. The distribution of the kinetic energy is that of a one-dimensional harmonic oscillator in thermal equilibrium, which is given by

$$p(E_{kin}) = \frac{1}{\sqrt{\pi}\sqrt{k_B T}} \frac{1}{\sqrt{E_{kin}}} \exp(-\frac{E_{kin}}{k_B T}).$$

This leads to a Gaussian velocity distribution for the axial degree of freedom

$$p(v) = \frac{1}{\sqrt{\pi}} \sqrt{\frac{m}{2k_B T}} \exp(-\frac{mv^2}{2k_B T}), \tag{2}$$

with a standard deviation of $\sigma_v = \sqrt{k_B T/m}$, where $m = 1.44 \cdot 10^{-25}$ kg is the mass of a ^{87}Rb atom. The first-order Doppler shift for the frequency ω is given by $\Delta\omega = \omega \cdot v/c$, and the standard deviation of the corresponding frequency distribution is then $\sigma_\omega = \omega \cdot \sigma_v/c$.

The temperatures of the atoms in the two traps were measured with different techniques. For the first trap the temperature was determined by a spectroscopic linewidth analysis giving $105\,\mu$K [13]. For the second trap it was measured by lowering the trap depth [16] yielding a temperature of $57\,\mu$K. These temperatures were measured directly after loading the atom into the trap. One has to keep in mind that during the repeated pumping/excitation procedure additional photons are scattered by the atoms leading to an increase of kinetic energy. However, as the pumping and excitation beams are applied orthogonally to the axis of the collection optics (which is also the axial direction of the trap) this influences only the radial degrees of freedom. The transfer of energy to the axial degree of freedom, where the oscillation frequencies are one order of magnitude smaller, is a slow process induced mainly by the anharmonicity of the trap. One burst of 20 pumping/excitation attempts takes $100\,\mu$s before additional cooling is applied, this is less than one axial oscillation period ($160..800\,\mu$s) and therefore the exchange of energy between the degrees of freedom is negligible. On average approximately 52 photons are scattered during the burst (1.6 photons for pumping and 1 per excitation attempt). The momentum diffusion which is caused by emission of 52 photon momenta into 4π solid angle corresponds to a standard deviation of roughly $4\hbar k$ per degree of freedom which is small compared to the thermal distribution. Thus the kinetic energy in the relevant axial degree of freedom practically does not increase during the pumping/excitation procedure.

Inserting the measured temperatures into (2) we arrive at frequency spreads $\sigma_{\omega,1} = 2\pi \cdot 128.5$ kHz for a photon emitted in the first trap and $\sigma_{\omega,2} = 2\pi \cdot 94.6$ kHz for the second. This results in a relative frequency spread between the photons emitted by the remotely trapped atoms of

$$\sigma_{\omega,rel} = \sqrt{\sigma_{\omega.1}^2 + \sigma_{\omega,2}^2} = 2\pi \cdot 159.6\,\text{kHz}. \tag{3}$$

D. Spectral overlap of the photonic wave packets

The obtained frequency differences of the two photons caused by Doppler shifts allow us to calculate the spectral overlap of the two interfering single photon wave functions. In order to simplify the calculation we assume that the excitations of both atoms are performed instantaneously and that the wave packets arrive simultaneously at the beam splitter at $t = 0$. Then their wave functions can be expressed as

$$\begin{aligned} |\psi_1\rangle(t) &= \frac{1}{\sqrt{\tau}} \exp(-\frac{t}{2\tau}) \exp(-i\omega_0 t) \\ |\psi_2\rangle(t) &= \frac{1}{\sqrt{\tau}} \exp(-\frac{t}{2\tau}) \exp(-i\omega_0' t) \end{aligned}$$

for $t \geq 0$, and $|\psi_{1,2}\rangle(t) = 0$ for $t < 0$, where $\tau = 26.2$ ns is the lifetime of the excited level $5^2P_{3/2}$ and ω_0, ω_0' are the center frequencies. The spectral overlap is given by

$$|\langle\psi_1|\psi_2\rangle|^2 = \frac{1}{1+\tau^2\Delta\omega^2}, \tag{4}$$

where $\Delta\omega = \omega_0 - \omega_0'$ is the difference in center frequencies of the two wave packets. Including the spread of the center frequencies (3) the expectation value of the spectral overlap is

$$\frac{1}{\sqrt{2\pi}\sigma_{\omega,rel}} \int_{-\infty}^{\infty} d(\Delta\omega) \frac{1}{1+\tau^2\Delta\omega^2} \exp(-\frac{\Delta\omega^2}{2\sigma_{\omega,rel}^2}) = 0.9993.$$

Thus the spread of the emission frequencies of the two photons can be neglected.

VII. CONCLUSION

In this paper we have analyzed the requirements for achieving high-fidelity interference of single photons emitted by two remotely trapped atoms. The necessary synchronization of two independent remote trap setups was obtained providing a temporal overlap of photonic wave packets in excess of 0.989. The spectral overlap of the wave packets was found to be limited by Doppler shifts caused by the thermal motion of the atoms in the traps. With the help of temperature measurements on the atoms in the traps this factor was calculated giving a spectral overlap of 0.9993. Finally, the beam splitter was analyzed, showing that it should allow an interference contrast of 0.998 due to perfect spatial mode overlap and only small imperfections in the splitting coefficients. One has to keep in mind that the fidelity of the actual atom-atom entanglement will be affected by many additional factors. These include purity of the generation of single photons which are entangled with the atoms, residual polarization errors during propagation through fibers, compensation of birefringence of the fiber beam splitter, etc. The results presented in this paper show that our system provides a highly accurate means for performing a Bell-state measurement on single photons emitted by remotely trapped atoms which is a major prerequisite for long-distance atom-atom entanglement [17].

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