# Observation of Entanglement of a Single Photon with a Trapped Atom

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(Received 13 October 2005; published 25 January 2006)

We report the observation of entanglement between a single trapped atom and a single photon at a wavelength suitable for low-loss communication over large distances, thereby achieving a crucial step towards long range quantum networks. To verify the entanglement, we introduce a single atom state analysis. This technique is used for full state tomography of the atom-photon qubit pair. The detection efficiency and the entanglement fidelity are high enough to allow in a next step the generation of entangled atoms at large distances, ready for a final loophole-free Bell experiment.

DOI: 10.1103/PhysRevLett.96.030404 PACS numbers: 03.65.Ud, 03.67.Mn, 32.80.Qk, 42.50.Xa

Entanglement is a key element for quantum communication and information applications [1]. Demonstrations of quantum computers with ions in linear chains nowadays almost routinely create deterministically any desired entangled state with up to eight ions [2]. The currently largest quantum processor consisting of some tens of (not yet distinguishable) qubits in a so-called cluster state was implemented with neutral atoms in an optical lattice [3]. For future applications such as quantum networks or the quantum repeater [4], it is mandatory to achieve entanglement also between separated quantum processors. For this purpose, entanglement between different quantum objects such as atoms and photons—recently demonstrated for ions and photons [5]—forms the interface between atomic quantum memories and photonic quantum communication channels [6], finally allowing the distribution of quantum information over arbitrary distances.

Atom-photon entanglement is not only crucial for many applications in long range quantum communication but is also the key element to give the final answer to Einstein's question on the real properties of nature [7]. Together with Podolsky and Rosen, he pointed out the inconsistencies between quantum mechanics and their ideal of a local and deterministic description of nature [8]. They implied that parameters of a physical system (local hidden variables), which might not—yet—be known to us, could solve the problem. Until now, the results of many experiments based on Bell's inequality [9] indicate that hidden variable theories would result in incorrect predictions and, thus, are not a valid description of nature [10–12]. But all these tests are subject to loopholes [11,13], and none so far could definitely rule out all alternative concepts.

Here we describe the observation of entanglement between the polarization of a single photon and the internal state of a single neutral atom stored in an optical dipole trap. For this purpose, we introduce a new state-analysis method enabling full state tomography of the atomic qubit. This now allows for the first time the direct analysis of the entangled atom-photon state formed during the spontaneous emission process. Moreover, we can show that the results achieved indeed suffice to test Einstein's objections.

Atom-photon entanglement can be prepared best by exciting an atom to a state which ideally has two decay channels ($\Lambda$ configuration). The hyperfine structure of $^{87}$Rb offers a good approximation to such a level scheme [Fig. 1(a)]. Excited to the $5\,^2P_{3/2}$, $F'=0$ hyperfine level, the atom can spontaneously decay into the three magnetic sublevels $|m_F=0,\pm 1\rangle$ of the $5\,^2S_{1/2}$, $F=1$ hyperfine ground level by emitting a photon at a wavelength of 780 nm.

If the emitted photon is $\sigma^+$-polarized, the atom will be in the state $|m_F=-1\rangle$. If the photon is linearly $\pi$-polarized, the atom will be in the state $|m_F=0\rangle$, and for $\sigma^-$ polarization we find the state $|m_F=+1\rangle$. Since the emitted photons are collected along the quantization axis, $\pi$-polarized light (emitted into a different spatial mode) is not collected. Therefore, only spontaneous decay into the states $|m_F=\pm 1\rangle$ is observed. As long as these emission processes are indistinguishable in all other degrees of freedom, one obtains a coherent superposition of the two decay possibilities, i.e., the maximally entangled state

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|m_F=-1\rangle|\sigma^+\rangle + |m_F=+1\rangle|\sigma^-\rangle). \quad (1)$$

Here in each of the terms the first ket describes the state of the atom and the second one the polarization of the photon. The quantum mechanical phase of the atom-photon state is well defined and follows from the Clebsch-Gordan coefficients of the transitions.

In our experiment, atoms are cooled from a shallow magneto-optical trap (MOT) into an optical dipole trap located in the center of the MOT [14]. For the dipole trap waist size of 3.5 $\mu$m, a collisional blockade mechanism ensures that only single atoms are captured [15].

When a single atom is loaded into the trap and its fluorescence is registered, the sequence entangling the atom

 

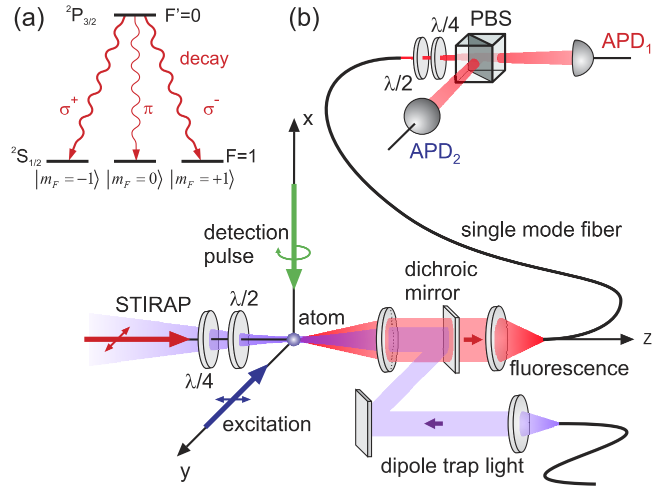


FIG. 1 (color online). (a) Preparation of atom-photon entanglement in $^{87}$Rb. The excited hyperfine level with $F' = 0$ can decay to three possible ground states with the magnetic quantum numbers $m_F = -1$, 0, or 1, by spontaneously emitting a $\sigma^+$, $\pi$, or $\sigma^-$ polarized photon, respectively. If the light is collected along the quantization axis, $\pi$-polarized photons are suppressed. Thus, an effective $\Lambda$ configuration is obtained which allows the preparation of a maximally entangled state between the photon polarization and the orientation of the atomic magnetic moment. (b) Scheme of the experimental setup. The dipole trap light ($\lambda = 856$ nm, $P = 30$ mW) is focused by a microscope objective (NA $= 0.38$) to a waist of 3.5 $\mu$m. The photon from the spontaneous decay is collected with the same objective, separated from the trapping beam by a dichroic mirror, and coupled into a single mode optical fiber guiding it to the polarization analyzer. The analyzer consists of a rotable half- and quarter-wave plate, a polarizing beam splitter (PBS), and two avalanche photodiodes (APD) for single photon detection. Triggered by the detection of the photon in either APD$_1$ or APD$_2$, the atomic state is analyzed using a STIRAP light field whose polarization defines the atomic measurement basis.

with a photon is started by pumping it into the $F = 1$, $m_F = 0$ state. Next, a 30 ns optical $\pi$ pulse excites the atom to the $F' = 0$ level, from which it will decay back to $F = 1$. Photons emitted along the quantization axis are collected and guided via a single mode optical fiber to a single photon polarization analyzer to determine the state of the photonic qubit [see Fig. 1(b)]. Because the emitted photon is detected with an overall efficiency of $\eta_{\rm ph} \approx 5 \times 10^{-4}$, the whole process has to be repeated approximately 2000 times to observe the photon. The repetition rate of this process is $1.25 \times 10^5$ s$^{-1}$. However, in the atomic state detection, the atom is lost with a probability of 0.5 (see below). Therefore, the mean time to load an atom into the dipole trap limits the total rate for the generation of entangled atom-photon pairs to 0.2 s$^{-1}$.

Once the emitted photon is detected, the state analysis of the atom is initiated. Standard spectroscopy techniques probing only the populations of the states $|m_F = -1\rangle$ and $|m_F = +1\rangle$ are not sufficient to confirm entanglement. Instead, a projection onto general superposition states is required. We thus apply a state selective stimulated Raman adiabatic passage (STIRAP) technique [16], which allows one to transfer an arbitrary superposition state $|\psi\rangle = \sin\theta|m_F = -1\rangle + e^{i\phi}\cos\theta|m_F = +1\rangle$ adiabatically to the $F = 2$ ground level (Fig. 2). Because of the selection rules of atomic dipole transitions, the orthogonal quantum state does not couple to the STIRAP light field $\Omega_1$ and remains in the $F = 1$ level. The angles $\theta$ and $\phi$ in this process are defined by the relative amplitude and phase of the $\sigma^+$ and $\sigma^-$ polarization components of the STIRAP laser $\Omega_1$, respectively. In essence, the polarization of the STIRAP laser defines which superposition state is transferred, thus allowing a full tomographic analysis of the atomic state without the necessity to perform any state manipulation on the atomic qubit.

After the STIRAP pulse, the atom is in a superposition of the hyperfine ground levels $F = 1$ and $F = 2$, which now can be distinguished by standard methods. We apply a detection laser pulse (resonant to the closed transition $F = 2 \rightarrow F' = 3$), removing atoms in the $F = 2$ level from the trap. Finally, to read out the atomic state, the cooling lasers of the MOT are switched on and atomic fluorescence is measured for 30 ms to decide whether the atom is still in the trap or not. Thereby, we obtain the binary result of the projective atomic state measurement on the state $|\psi\rangle$ and the orthogonal state $|\psi_\perp\rangle$. For the results shown in Fig. 3, we repeated the experimental cycle approximately 300 times per data point from which we obtain the probability of the atom to remain in $F = 1$ with a statistical error of $\pm 2\%$.

To verify the entanglement of the generated atom-photon state, we perform $\hat{\sigma}_x$ ($\theta = \pi/4$, $\phi = 0$) as well as $\hat{\sigma}_y$ ($\theta = \pi/4$, $\phi = \pi/2$) state analysis of the atomic qubit for different polarization measurements of the photon (Fig. 3, $\hat{\sigma}_i$ are the spin-1/2 Pauli operators). Thereby, the probability of the atom to be transferred by the STIRAP pulse sequence, or the probability to remain in the $F = 1$

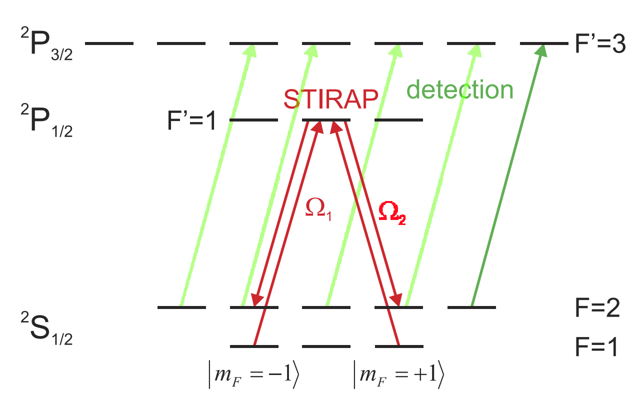


FIG. 2 (color online). Experimental procedure for the atomic state detection. To analyze the atomic state, a two-photon STIRAP-process state selectively transfers a superposition of the states $|m_F = -1\rangle$ and $|m_F = +1\rangle$ to the $F = 2$ hyperfine level. To read out the atomic qubit, a hyperfine-level selective detection pulse is applied before standard fluorescence detection.

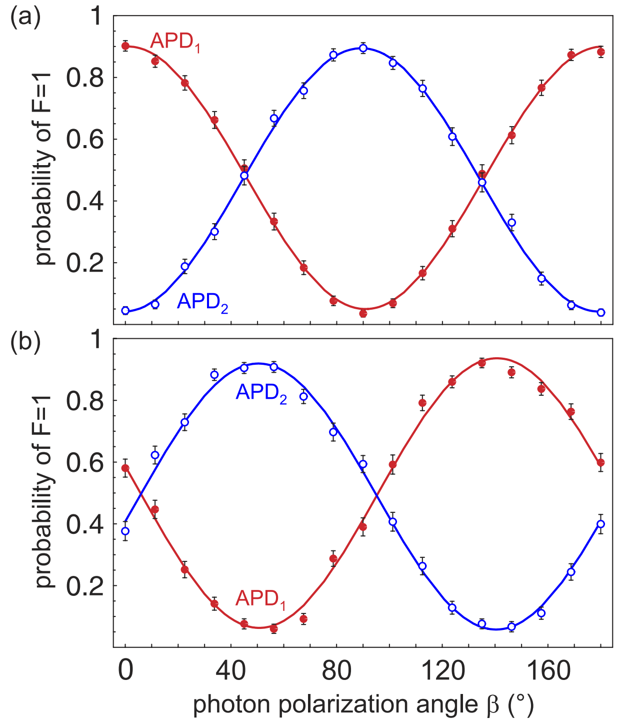


FIG. 3 (color online). Probability of detecting the atom in the ground level $F = 1$ (after the STIRAP pulse) conditioned on the detection of the photon in detector APD$_1$ (-●-) or APD$_2$ (-○-) as the linear polarization of the photonic qubit is rotated by an angle $\beta$. (a) The atomic qubit is measured in $\hat{\sigma}_x$ and (b) in $\hat{\sigma}_y$, whereas the photonic qubit is projected onto the states $1/\sqrt{2}(|\sigma^+\rangle \pm e^{2i\beta}|\sigma^-\rangle)$.

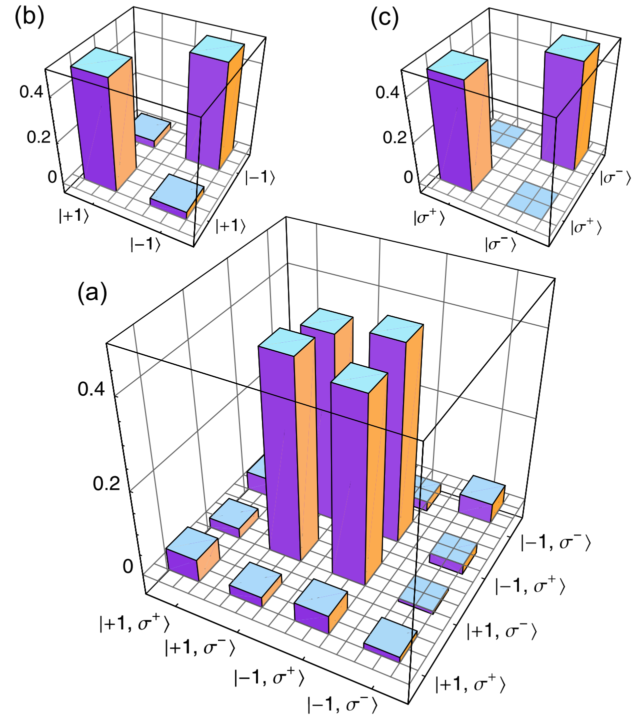


FIG. 4 (color online). (a) Graphical representation of the real part of the measured density matrix of the entangled atom-photon state. The fidelity (overlap with the expected state $|\Psi^+\rangle$) from this measurement is $\mathcal{F} = 0.87 \pm 0.01$. Insets (b) and (c) show the single particle density matrices for the atom and photon state, respectively, indicating that the single particles when observed on their own are found in a completely mixed state.

ground level, respectively, is measured, conditioned on the polarization measurement outcome of the photon. Varying the photon polarization analyzer, this probability shows the expected sinusoidal dependence for both $\hat{\sigma}_x$ and $\hat{\sigma}_y$. From the fits to the measured data, we obtain an effective visibility (peak to peak amplitude) of $V_{\text{at-ph}} = 0.85 \pm 0.01$ for analysis in $\hat{\sigma}_x$ and $V_{\text{at-ph}} = 0.87 \pm 0.01$ for analysis in $\hat{\sigma}_y$. This clearly proves entanglement of the generated atom-photon state.

For the determination of the full atom-photon state, we perform two-qubit state tomography. This involves a new set of measurements determining correlations of all combinations of the operators $\hat{\sigma}_x$, $\hat{\sigma}_y$, and $\hat{\sigma}_z$ on the atom and the photon [17]. The density matrix $\rho_{\text{at-ph}}$ determined this way clearly proves the state to be of the form of (1) [see Fig. 4(a)]. The fidelity, defined as the overlap between $|\Psi^+\rangle\langle\Psi^+|$ and $\rho_{\text{at-ph}}$, in this measurement was $\mathcal{F} = 0.87 \pm 0.01$. The limited visibility in the atom-photon correlations is caused mainly by errors in the atomic state detection (5%), accidental photon detection events due to the dark counts of the single photon detectors (3%), off-resonant excitation to the hyperfine level $5\,^2P_{3/2}$, $F' = 1$ (1%), and polarization errors of the STIRAP laser beams (2%). Applying the Peres-Horodecki criterion [18] to the combined density matrix proves the entanglement with a negativity of 0.382. Figures 4(b) and 4(c) show the density matrices of the atomic and the photonic state after tracing over the partner qubit. Obviously, these states are in a complete statistical mixture. However, it becomes clear that the resulting atom-photon state is *not* a mixture of all possible contributions but is instead a well defined (ideally) pure entangled state.

In view of these results, let us now analyze the performance of a possible loophole-free Bell experiment with a pair of entangled atoms. Crucial for such a test is a highly efficient state analysis by spacelike separated observers. To generate entanglement between atoms at remote locations, they are first entangled with a photon each. The two photons are brought together and then are subject to a Bell-state measurement, which serves to swap the entanglement to the atoms [19]. If we use the average visibility observed in our experiment and extrapolate results of recent two-photon interference experiments [20–22], we derive an expected atom-atom visibility of $V_{\text{at-at}} = V^2_{\text{at-ph}} = 0.74 \pm 0.01$. Thus, the violation of a Clauser-Horne-Shimony-Holt (CHSH)-type Bell inequality [23], which is achieved above the threshold visibility of 0.71, is feasible.

We emphasize that, triggered on the detection of a photon, every atomic state measurement yields a result. In this sense, the atomic detection efficiency is equal to one. In certain cases, as, e.g., the loss of the atom from the trap, a wrong measurement outcome may occur, but one always obtains a result. Moreover, entanglement swapping enables a so-called event-ready scheme [11,19,24]. If measurement results are reported for every joint photon detection event, this scheme is independent of any additional assumptions and, thus, is not subject to any detection related loopholes at all. To close at the same time the locality loophole, the atoms have to be spacelike separated with respect to the measurement time of the atomic states. The minimum distance of the atoms is determined by the duration of the atomic state detection. In detail, the atomic state collapses by scattering photons from the detection laser for 350 ns. Together with the STIRAP process, this yields an overall measurement time of less than 0.5 $\mu$s and requires a separation of the atoms of 150 m. Thus, we expect the generation of one entangled atom-atom pair per minute [25]. A loophole-free violation of a CHSH-type Bell's inequality [23] by 3 standard deviations would require approximately 7000 atom pairs at the expected visibility of 0.74. This would be feasible within a total measurement time of 12 days.

In this Letter, we presented a successful implementation of a source of high-fidelity entangled atom-photon pairs. We introduced a single atom STIRAP state analysis which does not require additional atomic state manipulations and, thus, can be performed with increased fidelity. This allowed us to perform the first full state tomography of an atom-photon system and proved that the spontaneous emission of the atom results in the entangled state $|\Psi^+\rangle$. In the experiment, we achieved a state fidelity of $\mathcal{F} = 0.87 \pm 0.01$ and a mean visibility of the atom-photon correlations of $V_{\text{at-ph}} = 0.86 \pm 0.01$. These methods, possibly combined with high-$Q$ cavities to enhance the collection efficiency [22,26], form the basic elements in future quantum information experiments for building the interface between quantum computers and a photonic quantum communication channel. In addition, these tools also help to find an answer to the long-standing question of whether local realistic extensions of quantum mechanics can describe nature at all. The experimental demonstration of high-fidelity entanglement provides the most important step towards a final, loophole-free test of Bell's inequality.

We acknowledge stimulating discussions with T. W. Hänsch and his group. This work was supported by the Deutsche Forschungsgemeinschaft and the European Commission through the EU Project QAP (IST-3-015848).

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