Entanglement is a key element for quantum communication and information applications. Demonstrations of quantum computers with ions in linear chains nowadays almost routinely create deterministically any desired entangled state with up to four ions and 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. For future applications like quantum networks or the quantum repeater it is mandatory to achieve entanglement also between separated quantum processors. For this purpose, entanglement between different quantum objects like atoms and photons – recently demonstrated for ions and photons – forms the interface between atomic quantum memories and photonic quantum communication channels, finally allowing the distribution of quantum information over arbitrary distances.

Atom-photon entanglement is not only crucial for the many application of 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. Together with Podolsky and Rosen he pointed out the inconsistencies between quantum mechanics and their ideal of a local and deterministic description of nature. They implied that parameters of a physical system (local hidden variables, LHV), which might not – yet – be known to us, could solve the problem. Until now, the results of many experiments based on Bell’s inequality indicate that hidden variable theories would result in incorrect predictions and thus are not a valid description of nature. But all these tests are subject to loopholes and none so far could definitely outrule 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 (Λ-configuration). The hyperfine structure of \(^{87}\text{Rb}\) offers a good approximation to such a level scheme (Fig. 1a). Excited to the \(^{2}\text{P}_{3/2}\), \(F' = 0\) hyperfine level, the atom can spontaneously decay into the three magnetic sublevels \(|m_F = 0, \pm 1\rangle\) of the \(^{2}\text{S}_{1/2}\) hyperfine level by emitting a photon at a wavelength of 780 nm. If the emitted photon is left circularly polarized (\(\sigma^-\)), the atom will be in the state \(|m_F = +1\rangle\), whereas we find \(|m_F = -1\rangle\) if the emitted photon is right circularly polarized (\(\sigma^+\)). Since the emitted photons are collected along the quantization axis, \(\pi\)-polarized light (emitted into a different spatial mode) is not collected for symmetry reasons and can be ignored. As long as the remaining \(\sigma^\pm\) emission processes are indistinguishable in all other degrees of freedom one obtains a coherent superposition of the two possible decay possibilities, i.e. the maximally entangled state

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

Here, in each of the terms the first ket describes the state of the atom, the second one the polarization of the photon. Although the quantum mechanical phase of this superposition follows from the Clebsch-Gordan coefficients of the transitions, it is generally not fully accepted that spontaneous emission should lead to a coherent superposition like (1) or whether not only a statistical mixture of the two possible emissions is formed. The tomography of the combined atom-photon state shows that this phase is indeed well defined.

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. For the dipole trap waist size of 3.5 \(\mu\text{m}\) a collisional blockade mechanism ensures that only single atoms are captured. 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)).

When a single atom is loaded into the trap and its fluorescence is registered, the sequence entangling the atom 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 $F = 1$. The emitted photon is detected with an overall efficiency of $\eta_{ph} \approx 5 \times 10^{-4}$. Thus, the whole excitation and emission process has to be repeated approximately 2000 times which, together with intermediate cooling cycles, results in an average rate of about 0.2 s$^{-1}$ observed atom-photon couples.

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 \cite{15, 16} which allows 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). Due to 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 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. 4 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 $\sigma_x$ ($\theta = \pi/4$, $\phi = 0$) as well as $\sigma_y$ ($\theta = \pi/4$, $\phi = \pi/2$) state analysis of the atomic qubit for different polarization measurements of the photon (Fig. 3). $\sigma_i$ are the spin-1/2 Pauli operators). Thereby, the
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 $\hat{\sigma}_x$; (b) in $\hat{\sigma}_y$, whereas the photonic qubit is projected onto the states $1/\sqrt{2}(|\sigma^+\rangle \pm e^{2i\beta}|\sigma^-\rangle)$.

probability of the atom to be transferred by the STIRAP pulse sequence, or the probability to remain in the $F = 1$ 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 $V = 0.85 \pm 0.01$ for analysis in $\hat{\sigma}_x$ and $V = 0.87 \pm 0.01$ 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 the measurement 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 $\rho_{\text{at}-\text{ph}}$ 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 $\rho_{\text{at}-\text{ph}}$, is $F = 0.87 \pm 0.01$. Applying the Peres-Horodecki criterion [18] to the combined density matrix proves the entanglement with a negativity of 0.382. Fig. 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 completely mixed states. This is what was observed with standard spectroscopy. However, from our experiment 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 space-like 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]. Starting with two entangled atom-photon pairs each in a state with visibility $V_{\text{at}-\text{ph}}$, the visibility of the entangled atom-atom state (after entanglement swapping) is ideally given by $V_{\text{at}-\text{at}} = V_{\text{at}-\text{ph}}^2$ [20]. If we use the average visibility observed in our experiment we thus derive an expected atom-atom visibility of $V_{\text{at}-\text{at}} = 0.74 \pm 0.01$. In comparison with related experiments [21, 22] we assume that the Bell-state analysis, required in the entanglement swapping process for narrowband photons and single-mode fibers, can be performed with a fidelity of better than 0.98. Thus, the violation of a Bell inequality, which is achieved above the threshold visibility of 0.71 for a CHSH-type Bell’s inequality [23], is feasible.

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 $F = 0.875 \pm 0.012$. Inset (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.
We emphasize, that triggered on the detection of a photon every atomic state measurement yields a result. In this sense, the detection efficiency (the probability to obtain a result from the atomic state measurement) here is equal to one. In certain cases, as e.g. the loss of the atom from the trap, the measurement might give wrong results reducing the visibility, but one always obtains a result. The raw data presented above of course contains such cases, nevertheless, the visibility is high enough. Moreover, entanglement swapping enables a so called event-ready scheme 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 space-like separated with respect to the measurement time of the atomic states. The minimum distance of the atoms is determined by the duration of the whole measurement sequence, here mainly given by the atomic state detection. In our experiment the superposition of the atomic hyperfine states collapses by scattering photons from the detection laser. After approximately 10 lifetimes ($\tau = 26$ ns) of the $^2P_{3/2}$ excited state the reduction of the initial superposition is completed with a probability of more than 99%. Together with the STIRAP-process this yields an overall measurement time of less than 0.5$\mu$s requiring a separation of the atoms of 150 m. The generation of entangled atom-photon pairs is probabilistic with a success probability given by the total detection efficiency $\eta_{ph}$ of the emitted photons. Taking into account transmission losses of the photons ($T^2(75m) = 0.9$), repetition rate for that distance: $5 \cdot 10^3 s^{-1}$) we expect the generation of about one entangled atom-atom pair per minute. Then, a loophole-free violation of e.g. a CHSH-type Bell’s inequality \footnote{K. Saucke, Optische Dipolfalle für Einzelatome (Diploma thesis, University of Munich, 2002); C. Simon and T. M. Irvine, Phys. Rev. Lett. 91, 110405-110408 (2003).} by three standard deviations, requiring approximately 7000 atom pairs at the expected visibility of 0.74, would be feasible with a total measurement time of 12 days.

In this contribution 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 $\ket{\Psi^+}$. In the experiment we achieved a state fidelity of $F = 0.87 \pm 0.01$ and a mean visibility of the atom-photon correlations of $V_{at-ph} = 0.86 \pm 0.01$. These methods, possibly combined with high-Q cavities to enhance the collection efficiency \footnote{M. Weber, Quantum optical experiments towards atom-photon entanglement (PhD thesis, University of Munich, 2005).}, 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 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.

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