Remote preparation of an atomic quantum memory

Wenjben Rosenfeld\textsuperscript{1}, Stefan Berner\textsuperscript{1}, Jürgen Volz\textsuperscript{1}, Markus Weber\textsuperscript{1}, and Harald Weinfurter\textsuperscript{1,2}

\textsuperscript{1}Department für Physik, Ludwig-Maximilians Universität München, D-80799 München, Germany
\textsuperscript{2}Max-Planck Institut für Quantenoptik, D-85748 Garching, Germany

Storage and distribution of quantum information are key elements of quantum information processing and quantum communication. Here, using atom-photon entanglement as the main physical resource, we experimentally demonstrate the preparation of a distant atomic quantum memory. Applying a quantum teleportation protocol on a locally prepared state of a photic qubit, we realized this so-called remote state preparation on a single, optically trapped $^{87}$Rb atom. We evaluated the performance of this scheme by the full tomography of the prepared atomic state, reaching an average fidelity of 82%.

Quantum teleportation\textsuperscript{1} and quantum cryptography\textsuperscript{2} were the first quantum communication methods experimentally demonstrated. Meanwhile, first devices for secure communication became already commercially available. For the next step of quantum information processing, new methods and technologies are required. Many new concepts of quantum information science, for example the quantum repeater\textsuperscript{3} or quantum networks, all the way towards distributed quantum computing, require a device interfacing photonic quantum channels and matter-based quantum memories and processors.

So far, there are two methods experimentally investigated. The first employs atomic ensembles to momentarily store quantum states of light. Recently, qubits encoded on single photons or qutits encoded in the quantum state of an electromagnetic field have been transferred to the collective state of atoms and vice versa\textsuperscript{4,5}. An impressive experimental demonstration of a first quantum communication protocol, the quantum teleportation of coherent states of light, was reported very recently\textsuperscript{6}.

In the second method the desired interface to a photonic communication channel can be realized using the recently achieved entanglement between a single atom and a single photon\textsuperscript{7-8}. This method applies directly to well-studied single quantum systems like trapped neutral atoms or ions. For linear ion chains and neutral atoms in optical lattices, various methods of quantum information storage and processing were already demonstrated, e.g. entanglement of up to 8 ions\textsuperscript{9,10}, creation of a cluster state involving tens of neutral atoms\textsuperscript{11}, or manipulations on a neutral atom quantum shift register\textsuperscript{12}. Furthermore, this interface concept can be adopted to other qubit systems, like optically addressed quantum dots\textsuperscript{13-15}, or superconducting QED-systems\textsuperscript{16}, stimulating novel applications in these areas as well.

Here we report the first experimental realization of a quantum communication protocol based on atom-photon entanglement. We perform full remote preparation of an atomic quantum memory via teleportation of an arbitrarily prepared quantum state of a single photon, using matter-light entanglement as the interface between the memory device and the communication channel. This method uses expansion of the Hilbert space of one particle of the entangled pair with subsequent complete Bell-state analysis. Being formally equivalent to quantum teleportation\textsuperscript{17-18} it enables the transfer of a known quantum state from the photon to the atom.

Figure 1: Schematic of atom-photon entanglement generation in a spontaneous decay of a single optically trapped $^{87}$Rb atom. (a) After optical excitation to $F' = 0$, the atom decays into the ground state manifold $|↑⟩_z, |↓⟩_z$ forming an entangled state between the atomic spin and the polarization of the emitted photon. (b) The emitted photon is collected with a microscope objective, coupled into a 5 m long single-mode optical fiber and guided to the preparation setup shown in Fig. 4. The overall detection efficiency for the photon is about $3 \times 10^{-4}$.

Recently, various approaches towards remote state preparation were studied experimentally with entangled photons\textsuperscript{19}, light beams\textsuperscript{20} and nuclear magnetic spins\textsuperscript{21}, however without expansion of the Hilbert space and without complete Bell-state analysis and thus with significantly reduced performance.

Our experiment includes four steps: (i) Entanglement is generated between the spin of a single trapped $^{87}$Rb atom and the polarization of a single spontaneously emitted photon\textsuperscript{8}. (ii) An additional degree of freedom of the photon is used to encode the quantum state we wish to transfer\textsuperscript{17}. (iii) The photon is subject to a complete Bell-state measurement\textsuperscript{18,22}, projecting the atom into one of four well-defined states. (iv) The success of the transfer is shown with full quantum state tomography of the atomic qubit.

In more detail, we first establish entanglement between a photon and a single neutral $^{87}$Rb atom stored in an optical dipole trap\textsuperscript{23}. Therefore the atom is optically excited to the $5^2 P_{3/2}, |F' = 0, m_{F'} = 0⟩$ state (see Fig. 1 (a)). In the following spontaneous decay the polarization of the emitted photon is entangled with the spin state of the atom\textsuperscript{8}, resulting in the maximally entangled state

$$|Ψ^⟩ = \frac{1}{\sqrt{2}}(|↓⟩_z |σ^⟩ + |↑⟩_z |σ^⟩),$$

(1)

where $|σ^⟩$ are the right- and left-circular polarization states of the emitted photon. The two states $|↑⟩_z$ and $|↓⟩_z$, defining
the atomic qubit, correspond to the \( F = 1 \), \( m_F = \pm 1 \) Zeeman sublevels of the \( 5S_{1/2} \) hyperfine ground level.

For the next step the emitted photon is coupled into a single-mode optical fiber (Fig. 1(b)) and guided to the setup shown in Fig. 2 where the state we wish to transfer is imprinted onto the photon. For this purpose we extend the Hilbert space of the photon by using two spatial modes as an additional degree of freedom. The photon is coherently split into the two spatial modes \(|a\rangle\) and \(|b\rangle\) by means of a polarization independent Mach-Zehnder interferometer, resulting in the spatial state \( \cos(\frac{\alpha}{2}) |a\rangle + \sin(\frac{\alpha}{2}) |b\rangle \). The phase \( \alpha \) is determined by the optical path-length difference between the two interferometer arms. Next, the two spatial modes acquire an additional phase difference \( \phi \), resulting in the state

\[
e^{i\phi} \cos(\frac{\alpha}{2}) |a\rangle + \sin(\frac{\alpha}{2}) |b\rangle
\]

of the photonic qubit. In order to prepare a well-defined state, precise control over the interferometric phases \((\alpha, \phi)\) is necessary. Therefore the optical path-length differences in the interferometric setup are actively stabilized with the help of an additional stabilization laser and an electronic feedback loop, allowing measurement times of up to 24 hours. By inserting a rotateable glass plate into the stabilization beam we can change these path-length differences and thus precisely control the phase setting.

Next, in order to transfer the state given by Eq. 4 onto the spin state of the atom, a Bell-state measurement in the polarization/spatial mode Hilbert space of the photon is performed. This is done by combining the two modes \(|a\rangle\) and \(|b\rangle\) on a polarizing beam-splitter and analyzing the photon polarization in each output port (see Fig. 2). The polarization analyzer detects \(|\pm \phi \rangle = \frac{\sqrt{2}}{2}(|H\rangle \pm |V\rangle)\) polarized photons by means of four single photon counting Si avalanche photo diodes (APD1-4). Since the PBS transmits horizontal \(|H\rangle\) and reflects vertical \(|V\rangle\) polarization, a coherent superposition of orthogonal polarizations from both modes is necessary to obtain \(|\pm \phi \rangle\) in the output of the PBS. For example to get \(|\pm \phi \rangle\) in the PBS output with detectors 1 and 2, \(|H\rangle\) polarization has to be transmitted from mode \(|b\rangle\) and coherently added to \(|V\rangle\) polarization reflected from mode \(|a\rangle\). This corresponds to the Bell-state \(|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|V\rangle |a\rangle + |H\rangle |b\rangle\). Accordingly, the \(|- \phi \rangle\) polarization corresponds to the \(|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|V\rangle |a\rangle - |H\rangle |b\rangle\) state, while in the other output of the PBS the states \(|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle |a\rangle \pm |V\rangle |b\rangle\) are detected.

The Bell-state detection projects the atomic qubit onto one of the four states

\[
|\Phi_1\rangle = e^{i\phi} \cos(\frac{\alpha}{2}) |\uparrow\rangle_x + \sin(\frac{\alpha}{2}) |\downarrow\rangle_x \\
|\Phi_2\rangle = e^{i\phi} \cos(\frac{\alpha}{2}) |\uparrow\rangle_x - \sin(\frac{\alpha}{2}) |\downarrow\rangle_x \\
|\Phi_3\rangle = e^{i\phi} \cos(\frac{\alpha}{2}) |\downarrow\rangle_x - \sin(\frac{\alpha}{2}) |\uparrow\rangle_x \\
|\Phi_4\rangle = e^{i\phi} \cos(\frac{\alpha}{2}) |\downarrow\rangle_x + \sin(\frac{\alpha}{2}) |\uparrow\rangle_x
\]

where \(|\uparrow\rangle_x, |\downarrow\rangle_x = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)\). State \(|\Phi_1\rangle\) is already equivalent to the photonic state from Eq. 4. The states \(|\Phi_2\rangle, |\Phi_3\rangle, \) and \(|\Phi_4\rangle\) can be transformed into \(|\Phi_1\rangle\) by applying the operation \(\sigma_x, \sigma_y, \) or \(\sigma_z\), respectively on the atom.

After completion of the transfer of the state from the photon to the atom we perform the analysis of the atomic state. First, a certain superposition of \(|\uparrow\rangle_x, |\downarrow\rangle_x\) is transferred to a different hyperfine level (\(|F = 2\rangle\)) by means of a state-selective STIRAP process. The polarization of the transfer pulse defines which superposition is being transferred and thus allows the choice of the measurement basis. The following hyperfine-state analysis measures the fraction of population which was transferred by removing atoms in the state \(|F = 2\rangle\) from the trap. This method allows to analyze the state of the atom in any desired basis and thus to reconstruct the density matrix of the state by combining measurements in 3 complementary bases. The characterization of the entangled atom-photon state with this method yields a fidelity of 87%.

In order to evaluate the performance of our preparation scheme, we prepared different states of the atom by varying the phase settings \((\alpha, \phi)\). Then we performed a full quantum state tomography of the atomic qubit for each of the four detected Bell states separately. Fig. 4 exemplarily shows a measurement where we set \(\alpha = 90^\circ\) while rotating \(\phi = 0^\circ...330^\circ\) in steps of \(30^\circ\). Let us consider, e.g., the state which is prepared when the photon is registered in detector APD1. This state can be decomposed in three complementary bases as

\[
|\Phi_1\rangle = \cos(\frac{\alpha}{2} (\phi + \frac{\pi}{2})) |\uparrow\rangle_z + i \cdot \sin(\frac{\alpha}{2} (\phi + \frac{\pi}{2})) |\downarrow\rangle_z = \cos(\frac{\alpha}{2} \phi) |\uparrow\rangle_y + i \cdot \sin(\frac{\alpha}{2} \phi) |\downarrow\rangle_y
\]

While the projections of \(|\Phi_1\rangle\) onto \(|\uparrow\rangle_x\) and \(|\downarrow\rangle_x\) are equal and constant, we observe a dependence on \(\phi\) for the projection onto \(|\uparrow\rangle_z\), \(|\downarrow\rangle_z\) and \(|\uparrow\rangle_y\), \(|\downarrow\rangle_y\). By combining all three
measurements we determined the density matrix of each prepared atomic state. From this we derived the fidelity (which is the probability to find the atom in the state expected from Eq. (3)) for each detector and every setting of \((\alpha, \phi)\). The mean fidelity over all points and all four analyzed Bell-states in this measurement is 82.6%. We performed 4 sets of measurements of this kind preparing various states on different circles on the Bloch sphere (see Fig. 3). Altogether, 42 different states were prepared with a mean fidelity of 82.2% (see Table I).

There are several sources of imperfections which affect the achieved preparation fidelity. The most important factors are the limited purity of the generated entangled atom-photon state and imperfections in the atomic state detection, yielding together a reduced entanglement fidelity of 87%. Taking into account this error source we get a corrected fidelity of \(0.82 \approx 94\%\) for the preparation/teleportation process alone. This value is limited by the finite visibility of the interferometer and Bell-state analyzer (about 90%), the mechanical instability of the interferometer and the residual birefringence of its components. The coherence of the prepared states decays on a time scale of about 10\(\mu\)s and does not influence the current measurement. This decay is caused solely by dephasing due to magnetic stray fields, resulting from instabilities of the magnetic field compensation. Longer coherence times can be achieved by using an improved compensation method.

The presented experiment demonstrates the faithful remote preparation of arbitrary quantum states of a single atom without the need of a direct interaction between the information carrier (photon) and the quantum memory (atom). Our implementation uses a quantum teleportation protocol to transfer the state of a photonic qubit onto the atom with an average preparation fidelity as high as 82%. The long coherence time of atomic ground states\([24]\) makes such a system well suited for future applications. In particular, the combination with recent achievements in experiments with trapped atoms and ions makes advanced schemes like quantum networks or the quantum repeater - almost - state of the art. One could employ systems with a few atoms, where some are used for tasks like computation, storage and entanglement purification, others for establishing the communication link to neighboring nodes via entanglement swapping. This way one profits from both, the high fidelity and flexibility of quantum logic operations on atoms or ions and the efficient transmission of photonic qubits that are ideally suited for efficient long distance distribution of quantum information.

This work was supported by the Deutsche Forschungsgemeinschaft and the European Commission through the EU Project QAP (IST-3-015848) and the Elite Network of Bavaria through the excellence program QCCC.

---

**Table I: Summary of the experimental results.** The table shows the fidelity \(F\), which is the probability of a successful state transfer, averaged over all 4 detected Bell-states and all 12 points within one measurement set.

| #  | \(\alpha\)  | \(\phi\)  | \(F\)         |
|----|-------------|-------------|---------------|
| 1  | 90°         | 0.330°      | 82.6% ± 0.40% |
| 2  | 0...330°    | 0°          | 79.7% ± 0.65% |
| 3  | 0...330°    | 90°         | 84.2% ± 0.45% |
| 4  | 109.5°      | 0.330°      | 82.2% ± 0.46% |

[1] C. H. Bennett et al. Phys. Rev. Lett. 70, 1895 (1993); D. Bouwmeester et al. Nature 390, 575 (1997); I. Marcikic et al. Nature 421, 509 (2003); M. Riebe et al. Nature 429, 734 (2004); M. D. Barrett et al. Nature 429, 737 (2004).
[2] N. Gisin, G. Ribordy, W. Tittel, H. Zbinden. Reviews of modern Physics 74, 145 (2002).
[3] H.-J. Briegel, W. Dür, J.I. Cirac, P. Zoller. Phys. Rev. Lett. 81, 5932 (1998).
[4] D. Matsukevich, A. Kuzmich. Science 306, 663 (2004).
[5] B. Julsgaard et al. Nature 432, 482 (2004).
[6] J. Sherson et al. quant-ph/0605095.
[7] B.B. Blinov, D.L. Moehring, L.M. Duan, C. Monroe. Nature 428, 153 (2004).
[8] J. Volz et al. Phys. Rev. Lett. 96, 030404 (2006).
[9] H. Häffner et al. Nature 438, 643 (2005).
[10] D. Leibfried et al. Nature 438, 639 (2005).
[11] O. Mandel et al. Nature 425, 937 (2003).
[12] Y. Miroshnychenko et al. Nature 442, 151 (2006).
Figure 4: Tomographic dataset of the prepared atomic states for $\alpha = 90^\circ$, $\phi = 0...330^\circ$. The figures show the probability $p$ to find the atom in the state $|\uparrow\rangle_z$ (left), $|\downarrow\rangle_x = \frac{1}{\sqrt{2}}(|\uparrow\rangle_z - |\downarrow\rangle_z)$ (middle) and $|\uparrow\rangle_y = \frac{1}{\sqrt{2}}(|\uparrow\rangle_z + i|\downarrow\rangle_z)$ (right), respectively, after a photon detection in detector 1 (red, filled) and 2 (blue, hollow) (upper row), 3 (green, filled) and 4 (magenta, hollow) (lower row). Each data-point is evaluated from 150-350 measurement processes from which we calculate the depicted statistical errors (one standard deviation). The mean fidelity of the 12 states prepared in this measurement is 82.6%. The acquisition of the full dataset was realized within approximately three days at an event rate of 10-20 per minute.

[13] X. Li et al. Science 301, 809 (2003).
[14] A. Badolato et al. Science 308, 1158 (2005).
[15] L. Childress et al. Phys. Rev. Lett. 96, 070504 (2006).
[16] A. Wallraff et al. Nature 431, 162 (2004).
[17] S. Popescu. quant-ph 9501020 (1995).
[18] D. Boschi et al. Phys. Rev. Lett. 80, 1121 (1998).
[19] N. Peters. et al. Phys. Rev. Lett. 94, 150502 (2005).
[20] S.A. Babichev, B. Brezger, A.I. Lvovsky. Phys. Rev. Lett. 92, 047903 (2004).
[21] X. Peng et. al. Phys. Lett. A 306, 271 (2003).
[22] M. Michler. PhD-thesis, University of Vienna (2000).
[23] M. Weber, J. Volz, K. Saucke, C. Kurtsiefer, H. Weinfurter. Phys. Rev. A 73, 043406 (2006).
[24] R.A. Cline, J.D. Miller, M.R. Matthews, D.J. Heinzen. Opt. Lett. 19, 207 (1994).