Entanglement of two individual atoms using the Rydberg blockade

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We report on our recent progress on the manipulation of single rubidium atoms trapped in optical tweezers and the generation of entanglement between two atoms, each individually trapped in neighboring tweezers. To create an entangled state of two atoms in their ground states, we make use of the Rydberg blockade mechanism. The degree of entanglement is measured using global rotations of the internal states of both atoms. Such internal state rotations on a single atom are demonstrated with a high fidelity.

1. Introduction

Entanglement has been proposed as a resource for quantum information processing, for quantum metrology, and for the study of quantum correlated systems. It has already been demonstrated in many systems, such as photons, ions, hybrid systems composed of an atom and a photon, atomic ensembles, and superconducting circuits. Regarding the entanglement of neutral atoms, so far two different approaches have been realized. One method relies on the interaction of transient Rydberg atoms with a high-finesse microwave cavity and results in entanglement of the atoms in different Rydberg states. The other approach uses s-wave collisions between ultra-cold atoms in an optical lattice. Here, we demonstrate a different approach to create entanglement of two individual atoms where we use the strong interaction of atoms when they are in a Rydberg state.
Atoms can be excited briefly to a Rydberg state where they can interact, and in this way their interaction can be switched on and off at will. This approach has been proposed theoretically in the context of quantum information processing\textsuperscript{12–16} and is in principle deterministic and scalable.

2. Single atoms in optical tweezers

In our experiment we use rubidium 87 atoms. A laser beam tightly focused down to the diffraction limit of a large numerical aperture lens (N.A. = 0.7) forms a dipole trap which acts as an optical tweezer, as shown in figure 1(a). The light field at the focal point of the lens is well approximated by a gaussian beam with a waist \( w = 0.9 \mu m \). The wavelength of the trapping laser is 810 nm, detuned by 15 nm with respect to the D1-line of rubidium at 795 nm. The trap depth is 1 mK for a power of 0.8 mW.

![Optical setup for single-atom trapping](image)

Fig. 1. (a) Optical setup for single-atom trapping. A homemade large numerical aperture objective consisting of 9 lenses focuses the tweezers light at 810 nm into an optical molasses. The same lens is used to collect the fluorescence light emitted at 780 nm by the atom. (b) Example of the fluorescence signal collected on an avalanche photodiode. The higher level of the steps in the count rate indicate that a single atom is trapped in the tweezer.

The dipole trap is loaded from an optical molasses. Atoms enter the trap randomly, and are laser-cooled by the molasses beams. We collect the fluorescence light of the atoms induced by the cooling lasers at 780 nm with the same large numerical aperture lens onto an avalanche photo-diode. We
observe discrete steps in the photon count rate, a lower level associated with background light and dark counts of the detectors and a higher level which we attribute to the presence of a single atom in the trap. Due to the tight trapping volume, two atoms cannot be captured at the same time in the tweezers as an inelastic light-induced collision expels both atoms immediately.\textsuperscript{17} We set a threshold to decide whether an atom is present or not. The detection of a single atom in the trap triggers the experimental sequence (see figure 1b).

In order to trap two single atoms in neighboring tweezers, we send through the same large numerical aperture lens two trapping beams with a small angle between them. The two traps are separated by 4 $\mu$m. Our imaging system is designed in such a way that the light coming from each trapped atom is directed onto separate avalanche photodiodes which allows us to discriminate for each trap whether an atom is present or not (figure 2a). The loading of both dipole traps is random and we capture on average every 0.5 s an atom in each of the tweezers at the same time.

![Fig. 2. (a) Optical setup for the collection of the light emitted by two atoms in different dipole traps separated by 4 $\mu$m (not shown). The lasers to excite the atoms in the Rydberg states are also shown. APD: avalanche photodiode. (b) Level structure of rubidium 87 and laser system used in the experiment.](image)

3. Single atom internal state manipulation

We consider the two hyperfine ground states $|\downarrow\rangle = |F = 1, M = 1\rangle$ and $|\uparrow\rangle = |F = 2, M = 2\rangle$ of the $5s_{1/2}$ level which are separated by $\hbar \times 6.8$ GHz
(figure 2b). We apply a 9 G magnetic field to lift the degeneracy between the Zeeman sublevels, so that $|↓⟩$ and $|↑⟩$ form a clean two-level system.

We drive the transition between these two states using a pair of laser beams in Raman configuration. Both lasers have a wavelength of 795 nm and are phase-locked to each other with a frequency difference of 6.8 GHz. They are blue detuned by 600 MHz with respect to the level $(5p_{1/2}, F' = 2)$. The two beams are copropagating and focused to a waist of 130 $\mu$m. The laser power is 40 $\mu$W in each beam resulting in a Rabi frequency of $2\pi \times 17$ MHz for each beam and a two-photon Rabi frequency $\Omega_{↑↓} = 2\pi \times 250$ kHz.

We measure the internal state of the atom using a push-out laser which is tuned to the transition from $(5s_{1/2}, F = 2)$ to $(5p_{3/2}, F' = 3)$. The push-out laser is applied on the atom before we check its presence in the trap by turning back on the molasses beams and observing the fluorescence. While an atom in state $|↑⟩$ will be expelled from the trap and is absent at the end of the sequence, an atom in state $|↓⟩$ will not be influenced by the push-out laser and is still present. We note that this method does not discriminate between Zeeman sublevels of the $F = 1$ and $F = 2$ manifold $5s_{1/2}$.

![Figure 3](image.png)

**Fig. 3.** Rabi oscillations between the states $|↓⟩$ and $|↑⟩$ with a Rabi frequency of 250 kHz. The line is a fit on the data with the model developed in reference.18

To perform an internal state rotation of a single atom, we apply the following experimental sequence. We start by pumping the atom in state $|↑⟩$ by applying a 600 $\mu$s long laser pulse, $\sigma_+$ polarized and tuned on the $(5s_{1/2}, F = 2)$ to $(5p_{3/2}, F' = 2)$ transition, together with a repumping laser tuned on the $(5s_{1/2}, F = 1)$ to $(5p_{3/2}, F' = 2)$ transition. We then apply the pair of Raman lasers for a given duration and finally detect the atomic
state with the push-out technique. We repeat this sequence 100 times and measure the probability to find the atom in state $|↓\rangle$. When varying the duration of the Raman pulse, we observe Rabi oscillations between the states $|↓\rangle$ and $|↑\rangle$, as shown in figure 3. Using the model developed in reference, we extract from the contrast of the oscillation an efficiency above 99% for the combined sequence of preparation, rotation and detection.

4. Rydberg blockade and entanglement

When an atom is in a Rydberg state (principal quantum number $n \gg 1$), one of its electrons is very far from the nucleus, typically at a distance $n^2a_0$ (with $a_0$ the Bohr radius). As a consequence the Rydberg atom develops a large electric dipole moment. Two of them will therefore interact strongly even at a distance of several micrometers. This strong interaction can be used to prevent the simultaneous excitation of two atoms into a Rydberg state, a mechanism known as the Rydberg blockade.

The principle of the blockade is shown in figure 4(a). Ground state $|↑\rangle$ and Rydberg state $|r\rangle$ are separated by an energy $E$. The spectrum of the two-atom system exhibits two degenerate transitions coupling $|↑, ↑\rangle$ to $|↑, r\rangle$ or $|r, ↑\rangle$ and these two states to $|r, r\rangle$. However, if the atoms are close enough the energy of the doubly excited state $|r, r\rangle$ is shifted by an amount $\Delta E$. Then the degeneracy is lifted and a laser excitation with a linewidth smaller than $\Delta E$ can not excite both atoms to the Rydberg state.

As a consequence of the blockade the two atoms behave collectively,
as illustrated in figure 4(b). If only one of the two atoms is excited, it is convenient to use the two entangled states $|\Psi_{R\pm}\rangle = \frac{1}{\sqrt{2}} (e^{i\mathbf{k} \cdot \mathbf{r}_a} |r, \uparrow\rangle \pm e^{i\mathbf{k} \cdot \mathbf{r}_b} |\uparrow, r\rangle)$ as a basis, where $\mathbf{r}_a$ and $\mathbf{r}_b$ are the positions of the two atoms, and $\mathbf{k}$ is related to the wavevectors of the exciting lasers. The state $|\Psi_{R-}\rangle$ is not coupled to the ground state, while the state $|\Psi_{R+}\rangle$ is coupled with an effective Rabi frequency $\sqrt{2} \Omega$, where $\Omega$ is the Rabi frequency between $|\uparrow\rangle$ and $|r\rangle$ of a single atom. In the blockade regime, where the state $|r, r\rangle$ is out of resonance, the two atoms can be described by an effective two-level system involving collective states $|\uparrow, \uparrow\rangle$ and $|\Psi_{R+}\rangle$ coupled with a strength of $\sqrt{2} \Omega$. Hence, the atoms are excited into an entangled state containing only one excited atom, with a probability which oscillates $\sqrt{2}$ times faster than the probability to excite one atom when it is alone.

To produce entanglement between the atoms in their ground states we start from $|\uparrow, \uparrow\rangle$ and apply a pulse of duration $\pi/(\sqrt{2} \Omega)$ which prepares the state $|\Psi_{R+}\rangle$. Then, the Rydberg state $|r\rangle$ is mapped onto the other ground state $|\downarrow\rangle$ using additional lasers (wave vector $\mathbf{k}'$, same Rabi frequency $\Omega$) with a pulse of duration $\pi/\Omega$. This sequence results in the maximally entangled state

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|\downarrow, \uparrow\rangle + e^{i\phi} |\uparrow, \downarrow\rangle),$$

with $\phi = (\mathbf{k} - \mathbf{k}') \cdot (\mathbf{r}_b - \mathbf{r}_a)$, assuming that the positions of the atoms are frozen during the applied pulse sequence. If the light fields are propagating in the same direction and the energy difference between the two ground states is small, $\mathbf{k} \simeq \mathbf{k}'$, we deterministically generate a well defined entangled state with $\phi = 0$ which is the $|\Psi^+\rangle$ Bell state.

5. Demonstration of Rydberg blockade between two atoms and collective excitation

We have chosen the Rydberg state $|r\rangle = |58d_3/2, F = 3, M = 3\rangle$. The interaction energy between two atoms in this state is enhanced by a Förster resonance which leads to a calculated interaction energy $\Delta E/h \approx 50$ MHz for a distance between the atoms of 4 $\mu$m.$^{19}$

We excite the atoms to the Rydberg state $|r\rangle$ by a two-photon transition. One of the excitation lasers has a wavelength of 795 nm and is detuned by several hundreds of MHz to the blue of the transition from $|\uparrow\rangle$ to the intermediate state $|5p_{1/2}, F = 2, M = 2\rangle$. The second laser has a wavelength of 474 nm and connects the intermediate state to the Rydberg state (see figure 2b). Both laser beams illuminate the two atoms. During the excitation
(<500 ns), the dipole trap is turned off to avoid an extra light-shift on the atoms. A successful excitation of an atom to the Rydberg state is detected through the loss of the atom when the dipole trap is turned back on, as atoms in the Rydberg state are not trapped in the tweezers.

Figure 5 shows the result of two experiments,\textsuperscript{19} where we apply the Rydberg excitation laser pulses either to a single atom or two neighboring atoms. In the first experiment, only one of the two dipole traps is filled with a single atom. We prepare the atom in state $|\uparrow\rangle$ and send the Rydberg excitation lasers for a given duration. Afterwards we measure if the atom is present (i.e. no Rydberg excitation) or absent (i.e. excited to the Rydberg state). We repeat the sequence 100 times to extract the excitation probability for a given pulse duration. We observe Rabi oscillations between state $|\uparrow\rangle$ and $|\downarrow\rangle$ at a frequency $\Omega = 2\pi \times 7$ MHz. The contrast is limited in this experiment by imperfect optical pumping, laser intensity and frequency fluctuations and spontaneous emission from the intermediate state. In the second experiment, we repeat the same sequence but this time we trap an atom in each of the two tweezers separated by 4 μm. At the end of each sequence we measure the presence or the absence of each atom and extract the probability to excite both atoms at the same time and the probability to excite only one of the two atoms. Figure 5 shows that the probability to excite both atoms is suppressed, as it is expected in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Demonstration of the Rydberg blockade between two atoms separated by 4 μm. The dots are the probability to excite one atom alone (second trap empty). The squares are the probability to excite the two atoms at the same time to the Rydberg state. They show a suppression of the excitation which indicates the blockade. The triangles are the probability to excite only one of the two atoms. It oscillates faster than for one atom alone due to the collective behaviour.}
\end{figure}
the blockade regime. At the same time the probability to excite only one of
the two atoms oscillates faster than the Rabi oscillation of a single atom.
The ratio of the two frequencies is 1.38, compatible with the expected \( \sqrt{2} \),
and is indicative of the collective behavior of the two atoms explained in
section 4.

We note a related experimental demonstration of the blockade, comple-
mentary to our approach.\(^{20}\)

6. Entanglement of two individual atoms

We start by preparing the two atoms in the state \( |↑,↑⟩ \) and we apply the
Rydberg excitation pulse of duration \( \pi/(\sqrt{2} \Omega) \). We then map the coherence
produced between the states \( |↑⟩ \) and \( |r⟩ \) onto the two hyperfine states \( |↑⟩ \)
and \( |↓⟩ \) by applying on both atoms a second pulse of duration \( \pi/Ω \), as
explained in section 4. For this mapping, we use the same 474 nm laser and
an additional laser at 795 nm, as shown in figure 2(b).

After sending the two laser pulses we measure the state of the atoms
using the push-out technique described in section 3. We assign the label 0
when the atom is lost at the end of the sequence and the label 1 when it is
still trapped. We measure at the end of the mapping sequence the two-atom
probabilities \( P_{11} = 0.06, P_{01} = 0.34, P_{10} = 0.31 \) and \( P_{00} = 0.29 \). In the
ideal case, the preparation of the state \( |Ψ^+⟩ \) should lead to \( P_{11} = P_{\uparrow\uparrow} = 0,\)
\( P_{01} = P_{\uparrow\downarrow} = 1/2, P_{10} = P_{\downarrow\uparrow} = 1/2 \) and \( P_{00} = P_{\downarrow\downarrow} = 0. \)

The fact that \( P_{00} \) is much larger than expected comes from extra losses
during the entangling sequence which we can not discriminate from atoms in
state \( |↑⟩ \) since the push-out state detection technique is also based on atom
loss. Different processes contribute to the loss from the logical states, e.g.,
spontaneous emission from the intermediate state \( |5p_1/2,F = 2,M = 2⟩ \),
resulting in atoms being depumped in state \( |5s_1/2,F = 2,M = 1⟩ \), or from
atoms staying in the Rydberg state resulting in atom loss. Intensity and
frequency fluctuations of the excitation lasers also prevent perfect excita-
tion of the atoms. The non-zero value of \( P_{11} \) is explained by spontaneous
emission from state \( |5p_1/2,F = 2,M = 2⟩ \) as well as from an imperfect
blockade.

In an independent measurement we have determined the atom loss dur-
ing the sequence. Reference\(^{21}\) gives more details on this study. We have
measured a probability \( p \approx 0.22 \) to lose one atom during the entangling
sequence. This leads to a probability to lose at least one of the two atoms
of \( 2p(1−p)+p^2 \approx 0.39 \). That means, from 100 experimental runs in average
we end up 61 times with both atoms in the logical states.
In order to analyze the amount of entanglement, we apply global Raman rotations on the two atoms before measuring their state. We vary the duration of the Raman pulse and extract the probability \( P_{11}(\Omega_{\uparrow\downarrow}t) \) as shown in figure 6. The probability \( P_{11}(\Omega_{\uparrow\downarrow}t) \) includes only events where both atoms are recaptured at the end of the entangling and rotation sequence, and is therefore of particular interest. We calculate from a model \( P_{11}(0) = P_{\downarrow\downarrow} \) and \( P_{11}(\pi) = P_{\uparrow\uparrow} \). A more detailed analysis of the evolution of \( P_{11}(\Omega_{\uparrow\downarrow}t) \) for various Raman pulse duration is explained in reference. The average value of \( P_{11}(\Omega_{\uparrow\downarrow}t) \) is related to the fidelity of the state with respect to the expected \( |\Psi^+\rangle \) Bell state, which is defined as \( F = \langle \Psi^+ | \hat{\rho} | \Psi^+ \rangle \), with \( \hat{\rho} \) the density matrix describing the two-atom system. From the data we extract a fidelity of the entangling sequence \( F = 0.46 \). This value is lower than the threshold of 0.5 which has to be overcome to prove the quantum nature of the correlations. However, this fidelity takes into account all events, even those for which one of the two atoms, or both, are lost from the logical states at the end of the sequence. To retrieve an entanglement fidelity of the remaining pairs of atoms, we calculate a renormalized fidelity of \( F' = F / 0.61 \approx 0.75 \). This value is larger than the required threshold for a Bell’s inequality test, had we a way to post-select on the events where only pair of atoms is present.

In our experimental implementation the value of the fidelity is currently limited by spontaneous emission, as well as laser intensity and frequency...
fluctuations. The residual motion of the atoms between the two entangling pulses, which in principle does not allow one to consider the atomic motion as frozen, as was done in section 4, causes only a small reduction of the observed fidelity.

7. Conclusion

In this paper we demonstrated our ability to manipulate the internal state of a single atom trapped in an optical tweezer and to control the interaction between two atoms in neighboring traps. The internal state of a single atom can be prepared with a high fidelity using Raman rotations. The interaction between the atoms is controlled using laser excitation towards a Rydberg state and manifest itself in the observation of the Rydberg blockade effect. We make use of this effect to create the entanglement of two atoms in two hyperfine ground states. Ongoing work is devoted to the improvement of the fidelity of the entangling operation.

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