Fast Entanglement Distribution with Atomic Ensembles and Fluorescent Detection

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Published Version</td>
<td>doi:10.1103/PhysRevA.81.020303</td>
</tr>
<tr>
<td>Citable link</td>
<td><a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:5385446">http://nrs.harvard.edu/urn-3:HUL.InstRepos:5385446</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at <a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP">http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP</a></td>
</tr>
</tbody>
</table>
Fast Entanglement Distribution with Atomic Ensembles and Fluorescent Detection

J. B. Brask, L. Jiang, A. V. Gorshkov, V. Vuletic, A. S. Sørensen, and M. D. Lukin

1 QUANTOP, The Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen Ø, Denmark
2 Department of Physics, Harvard University, Cambridge, MA 02138, USA
3 Institute for Quantum Information, California Institute of Technology, Pasadena, CA 91125, USA
4 Harvard-MIT Center for Ultracold Atoms, Department of Physics, MIT, Cambridge, MA 02139, USA

(Dated: November 9, 2009)

Quantum repeaters based on atomic ensemble quantum memories are promising candidates for achieving scalable distribution of entanglement over long distances. Recently, important experimental progress has been made towards their implementation. However, the entanglement rates and scalability of current approaches are limited by relatively low retrieval and single-photon detector efficiencies. We propose a scheme, which makes use of fluorescent detection of stored excitations to significantly increase the efficiency of connection and hence the rate. Practical performance and possible experimental realizations of the new protocol are discussed.

PACS numbers: 03.67.Hk, 03.67.Bg, 42.50.-p

Distribution of entanglement over long distances has diverse potential applications, ranging from absolutely secure cryptography to fundamental tests of quantum mechanics [1]. The task is challenging since direct transmission of quantum states via optical fibres suffers from exponential attenuation, rendering communication beyond a few hundred kilometers impossible. The losses can be overcome by implementing a so-called quantum repeater architecture, which divides a channel into small segments and combines quantum memories, entanglement swapping and entanglement purification to extend entanglement generated over these segments to longer distances [2]. Spurred by the proposal of Ref. [2] (DLCZ), a number of promising quantum repeater protocols based on storage of light in atomic ensembles have recently been put forward [3-6, 8]. Apart from atomic ensembles, these schemes require only simple linear optical operations and photodetection. They therefore lend themselves well to experimental realization, and extensive progress has been made towards their implementation [3, 5, 6, 10, 11, 12].

An important limiting factor in all existing atomic ensemble-based quantum repeater schemes is the efficiency of entanglement swapping, which requires conversion from excitations stored in atoms to light followed by single-photon detection. In practice, the combined retrieval and photodetection efficiency is on the order of ten percent [3, 9]. This severely limits the communication rates and thus the scalability of the existing approaches. Here we present a new ensemble-based quantum repeater, which circumvents this problem by storing multiple excitations in a single atomic ensemble, as in Ref. [13]. Entanglement swapping is achieved by fluorescent detection of the populations of certain atomic levels, eliminating the need for retrieval. Fluorescent detection can have very high efficiency and at the same time allows us to determine the number of stored excitations. For trapped ions, fluorescent detection efficiencies of 99.99% have been experimentally demonstrated [14], and similar techniques have been proposed for photon counting using ensemble-based memories for light [15, 16]. Employing such an idea allows the success probability for entanglement connection to be notably enhanced. Our protocol can be implemented either as a single-rail scheme (analogous to the original DLCZ scheme) or as a dual-rail scheme (analogous to the proposals of Refs. [4, 5]). Below we will focus on the single-rail scheme for simplicity, but we stress that the protocol may readily be extended to dual-rail, including entanglement purification [17].

As illustrated in Fig. 1, in our approach, repeater nodes separated by a distance $L_0$ each contain a single ensemble of $N$ atoms encoding two qubits via the level...
structure shown in Fig. 1b). Each atom has a reservoir level, two storage levels, henceforth denoted by ‘red’ and ‘blue’, and at least one cycling transition to an excited state which allows populations to be measured. Connecting to previous ensemble-based repeaters based on Λ-scheme atoms, one may think of Fig. 1b as a double Λ-scheme – one for each storage level – with two additional cycling transitions [3,4,5]. As discussed below, the proposed level scheme can be implemented in alkali or alkaline earth atoms. Every ensemble is initialised in the ‘vacuum’ state $|g\rangle^\otimes N$ with all $N$ atoms in the reservoir. To entangle two ensembles (Fig. 2a) we focus first on their blue levels. In each ensemble, a weak laser pulse induces Raman scattering, preparing a joint state of the atoms and the forward scattered Stokes light mode [2]

$$\left(1 + \sqrt{q\eta} \hat{s}_b^\dagger \hat{a}^\dagger\right) |\text{vac}\rangle + O(\eta\eta),$$

where $\hat{s}_b^\dagger = \frac{1}{\sqrt{N}} \sum_i |s_b\rangle_i |g\rangle$ creates a symmetric atomic spin wave, $\hat{a}^\dagger$ creates a Stokes photon, $|\text{vac}\rangle$ is the joint vacuum state of atoms and light, $q$ is the excitation probability and $\eta$ is the fraction of light scattered into the forward mode. The Stokes photons are then mixed on a balanced beam-splitter, and conditioned on the detection of a single click at the output ports, the ensembles are projected to an entangled state of the form

$$\left(\hat{s}_{b,1}^\dagger + \hat{s}_{b,2}^\dagger\right) |\text{vac}\rangle,$$

where $1,2$ label the ensembles. In this manner entanglement can be established at every other link of the repeater. To entangle the remaining links, the process is repeated using the red levels. For just three ensembles, the resulting state is

$$\left(\hat{s}_{r,2}^\dagger + \hat{s}_{r,3}^\dagger\right) \left(\hat{s}_{b,1}^\dagger + \hat{s}_{b,2}^\dagger\right) |\text{vac}\rangle.$$ 

This ideal scenario is implemented if we can avoid multiple excitations of the symmetric spin wave, which is the case when $\eta\eta \ll 1$. Also note that in addition to forward scattering described by Eq. 1, excitation of non-symmetric atomic modes occurs with probability $(1 - \eta\eta)q$. We analyze the contribution from these excitations below. Once two neighbouring entangled links are established they are connected by entanglement swapping (Fig. 2b). A $\pi/2$ rotation is applied between the two storage levels in the central ensemble, and the populations of these levels are then measured by fluorescent detection. Conditioned on the detection of a single excitation in either the red or the blue level, the outermost ensembles are projected to an entangled state. Referring to Eq. 4, the rotation acts like a beam splitter on the atomic operators taking $\hat{s}_{i,2}^\dagger \rightarrow (\hat{s}_{b,2}^\dagger + (-1)^{\hat{s}_{r,2}} \hat{s}_{r,2}^\dagger) / \sqrt{2}$, where $i = b, r$. The subsequent fluorescent detection effectively projects one atom from the central ensemble into $|s_r\rangle$ or $|s_b\rangle$ while the remaining atoms are projected to the reservoir state. As a result, up to a known phase flip ensembles 1 and 3 are projected to the entangled state

$$\left(\hat{s}_{b,1}^\dagger + \hat{s}_{r,3}^\dagger\right) |\text{vac}\rangle.$$ 

In the absence of imperfections the probability for a single atom to fluoresce is $2N/(4N - 1) \sim 1/2$, and hence the ideal probability for entanglement connection to succeed is $1/2$ as in previous schemes. However, since the DLCZ-protocol requires conversion from atomic to optical excitations and subsequent single-photon detection, it has much higher loss in practice than the present scheme.

Because the same atoms encode several qubits and because of the use of fluorescent detection, several issues not present in previous protocols must be considered in our scheme. First, fluorescent detection does not selectively detect the symmetric spin wave. This is in contrast to schemes based on retrieval, for which collective enhancement ensures that only excitations associated with Stokes photons scattered forward during entanglement generation will be detected during connection [3]. As a consequence, multieexcitation errors occur in our scheme with probability $q$ as opposed to $\eta\eta$ in previous schemes. To reach a given final fidelity the generation success probability, and thus the rate, must therefore be decreased by a factor of $\eta$, unless corrective measures are taken.

Specifically, to suppress excitations in modes other than the symmetric mode, one can use purification by interrupted retrieval (PIR) based on electromagnetically induced transparency. The behavior of a spin wave excitation with momentum $k$ under retrieval depends on the optical depth $d_k$ in the direction $k + k_c$, where $k_c$ is the control field wave-vector. The symmetric spin wave has $k \sim 0$ and for an elongated ensemble, we can arrange that $d_0 = d$, where $d \gg 1$ is the on-axis optical depth. Hence if we were to retrieve the symmetric spin wave from one of the storage levels by applying a control field to the $s \rightarrow e$ transition (dropping subscripts), the retrieved field would travel with the group velocity $v_g = \Omega^2 l / \gamma d$, where $\Omega$ is the Rabi frequency of the control field, $\gamma$ is the decay rate of the excited level, and $l$ is the length of the ensemble [3]. In other words, retrieval is highly directional and the field travels at a group velocity inversely proportional to $d$. On the other hand, for excitations with sufficiently small $d_k$, this picture is not valid. When $d_k \lesssim 1$, the excitation will decay without any directionality at the rate of a single emitter $\Omega^2 / \gamma$, where $\Omega \ll \gamma$. By placing the ensemble in a cavity or inside a hollow-core photonic crystal fibre, as discussed below, we can arrange that only a few modes have high $d_k$. E.g. in an hollow-core fibre, only the guided and near-transversal modes persist, while intermediate modes are suppressed. It is then possible to turn on the control.
field for a duration $T$ such that
\[ \frac{I}{v_p} \gg T \gg \frac{\gamma}{\Omega^2}. \] (5)

This means that the retrieval is interrupted before the
symmetric spin wave leaves the ensemble, while excita-
tions in other modes escape. Clearly there will be a
trade-off between loss of the symmetric spin wave and
suppression of the incoherent excitations. One can show
that the fraction of the symmetric spin wave lost is at
most $\delta = 2n/\sqrt{T}/I$, where half of the loss is simply the
retrieved field in the forward direction while the sec-
second half comes from spontaneous decay [17]. The excita-
tions in all other modes are suppressed by a fac-
tor $\eta + (1 - \eta)e^{-\delta t/d}$, and thus reducing the multi-
excitation error probability in our scheme to $O(\eta\gamma)$ costs
$\delta \sim -2\log(\eta)/d$. The loss probability $\delta$ and the
inefficiency of fluorescent detection can be regarded as a
connection inefficiency, equivalent to the combined re-
trieval and detection losses in previous schemes (where
retrieval loss scales with $d^{-1/2}$ [18]). For reasonable op-
tical depths $d \gtrsim 100$ and a forward scattering probability
$\eta$ at or above the percent level, $\delta$ is less than ten per-
cent. This is in contrast to state of the art conventional
approaches, in which losses are on the order of 90% or
more. Hence, even with PIR the total connection loss in
our scheme is significantly lower than the corresponding
losses in schemes with full retrieval.

Two additional imperfections lead to constraints on $N$.
Fluorescent detection implies an upper bound, because
measurements will exhibit high dark counts if the num-
ber of atoms in the reservoir is too large [13, 16]. Pop-
ulation in the reservoir can contribute to dark counts in
two ways. Either through off-resonant scattering on the
$g \leftrightarrow e$ transition of light from the probe field, which is
resonant with the cycling transition, or through popula-
tion transfer into $|s\rangle$ caused by the probe. Except when
the branching ratio $\beta$ for decay from $|e\rangle$ to $|s\rangle$ is tiny,
the latter of these provides a more severe restriction on the
atom number, because it is amplified by subsequent
resonant scattering. For simplicity we assume that the
two transitions have the same dipole moment, such that
we can associate a single Rabi frequency $\Omega_p$ with the
probe field, and that the decay rates from both excited
states are $\gamma$. The fluorescent scattering rate $r$ and the
scattering rate $r'$ from $|g\rangle$ into $|s\rangle$ are then given by
\[ r = \frac{\gamma \Omega_p^2}{\gamma^2 + 2\Omega_p^2}, \]
\[ r' = \frac{\beta \gamma \Omega_p^2}{4\Delta^2}, \] (6)
where the frequency difference between the $g \leftrightarrow e$ and cy-
cling transitions, denoted by $\Delta$, is much larger than both
$\Omega_p$ and $\gamma$. The rates $r$ and $r'$ determine the measure-
ment time and the amount of population transferred from
reservoir to storage level during that time, respectively.

The time required to faithfully detect a single excitation
in the storage level via fluorescent detection is $n/\eta_d\sigma$
where $\eta_d$ is the single photon detection efficiency and $n$
is the desired average number of measured photons. The
expected number of logical dark counts, i.e. the amount of
population transferred during the measurement, is
\[ \frac{N r' n}{\eta_d \sigma} = \frac{n \beta \gamma^2 + 2\Delta^2}{4\Delta^2} N. \] (7)

Clearly, it is desirable to implement our scheme in a sys-
}
\( d \sim 100 \) with \( 2 \cdot 10^3 \) atoms. Fluorescence measurements can be done on the D2-line cycling transition, which has \( \gamma = 6\text{MHz} \), and the reservoir can be separated from the detected level by the ground state hyperfine splitting \( \Delta = 6.8\text{GHz} \). Taking, for instance, \( \eta = 0.05 \), \( \eta_d = 0.5 \), \( n = 20 \), and \( \beta = 0.5 \), we find that with a single connection, an entangled state between nodes separated by 10km can be created. Taking atoms with a higher nuclear spin, e.g. \( ^{87}\text{Rb} \), such entangled ensembles can be used as a backbone for implementing the entire repeater chain, provided that advanced protocols including purification are employed. Higher fidelity implementations can be achieved with alkaline earth atoms. Alkaline earths are very well suited for implementation due to the presence of long-lived metastable levels which make it possible to separate the cycling transition from any transitions involving the reservoir by optical frequencies. E.g. in \( ^{87}\text{Sr} \), by cycling on the \( ^1S_0 \rightarrow ^1P_1 \) transition while keeping the reservoir temporarily in \( ^3F_1 \) we can have \( \Delta \approx 10\text{THz} \), while \( \gamma = 30\text{MHz} \). In addition it can be arranged that measurements do not induce population transfer from the reservoir into the cycling transition, such that only off-resonant scattering can contribute to dark counts. This means that the factor \( n_2/\eta_2 \) can be dropped from Eq. (7), relaxing the upper bound further. At the same time, if excitation and decay \( ^3P_0 \rightarrow ^1P_1 \rightarrow ^1S_0 \) is used for entanglement generation, the mismatch error can be suppressed by a very large branching ratio \( 1 - \beta \sim 10^{-5} \), so the lower bound is simply \( 1/\eta \). For a repeater over 1000km with \( 2^\theta \) segments and final fidelity \( F > 95\% \), we estimate an upper bound of \( \sim 10^4 \) while the lower bound above gives \( \sim 1 \). Thus, a repeater might be implemented with \( N \sim 10^4 \) atoms compatible with good optical depth. We note that while the upper bound for alkali earths is high enough to allow large \( d \) to be reached in free space, PIR requires that only a few nearly symmetric modes see high optical depth. Thus even for large \( N \) it is desirable to enclose the ensemble in a low-finesse cavity, enhancing \( d \) for the symmetric mode, or in a single-mode hollow-core fibre, since without PIR our rate would be suppressed by a factor \( \eta \), which is small in free space. Another promising candidate for implementation may be cavity enclosed crystals of ions with long-lived excited levels, e.g. \( \text{Ca}^+ \) or \( \text{Sr}^+ \). Strong collective coupling in such a system has recently been demonstrated. 

In summary, we have described a new ensemble-based quantum repeater protocol that uses fluorescence detection to significantly improve the efficiency of entanglement swapping. Our scheme can be implemented with atoms in a single-mode hollow-core fibre or a low-finesse cavity and yields improvements in communication rate for a distance of 1000km by two to four orders of magnitude over previous proposals. An interesting extension of our scheme would be to incorporate non-linearities such as Rydberg blockade.

We acknowledge helpful discussions with I. Cirac, E. Polzik, M. Bajcsy and S. Hofnerth. This work was supported by NSF, CUA, DARPA, the EU FET-Open project COMPAS (212008), and the Danish National Research Foundation.

---