Entangling Single Atoms Over 33 km Telecom Fibre

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Abstract

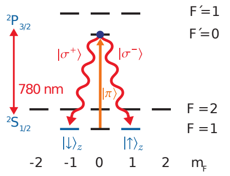
Quantum repeaters will allow scalable quantum networks, which are essential for large scale quantum communication and distributed quantum computing. A crucial step towards a quantum repeater is to achieve heralded entanglement between stationary quantum memories over long distances. To this end, we present results demonstrating heralded entanglement between two Rb-87 atoms separated by 400 m line-of-sight, generated over telecom fibre links with a length up to 33 km [1].

To entangle the two atoms, we start with entangling the spin state of each atom with the polarisation state of a photon in each node via synchronised excitations during the spontaneous decay. The emitted photons (780 nm) are then converted to the low loss telecom S band (1517 nm) via a polarisation preserving frequency conversion to overcome high attenuation loss in optical fiber [2].

The long fibre links guides these photons to a middle station where a Bell-state measurement swaps the entanglement to the atoms. Finally, the atomic states are analysed after a delay that allows for two-way communication between the nodes and the BSM over the respective fibre length. We observe loss in fidelity for longer fibre links due to the limited atomic coherence time.

Methods

• Atom-Photon Entanglement



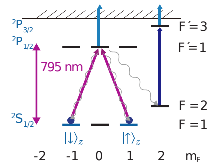
$$|\Psi_{AP}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_z|\sigma^+\rangle + |\uparrow\rangle_z|\sigma^-\rangle\right)$$

• Atom-Atom Entanglement

Entanglement swapping between two atom-photon pairs at BSM in H/V basis:

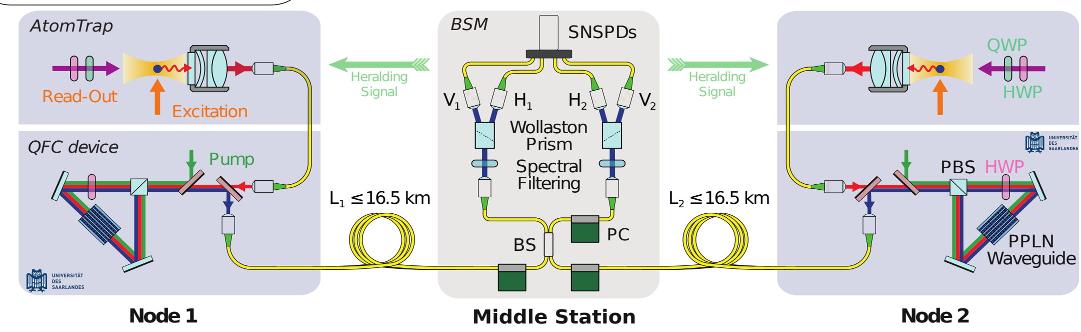
$$|\Psi_{AA}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_x|\uparrow\rangle_x + |\uparrow\rangle_x|\downarrow\rangle_x\right)$$

• Atomic State Readout



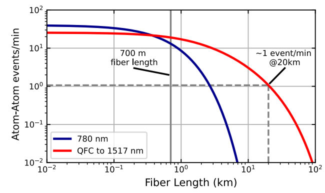
$$\chi_r = \cos(\alpha)V - e^{-i\phi}H$$

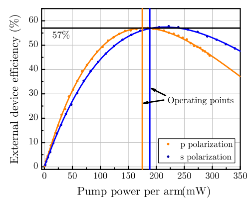
Experimental Setup



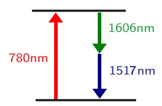
Quantum Frequency Conversion (QFC)

• Event Rate over Fiber Length





• Polarisation Preserving QFC [2]



-Difference frequency generation in PPLN waveguide:-

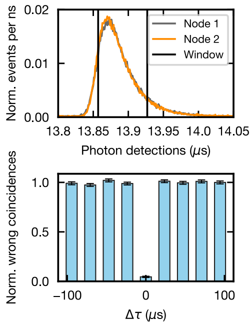
$$\omega_{1517\,nm} = \omega_{780\,nm} - \omega_{1606\,nm}$$

-External device efficiency of 57%

-Spectral filtering with cavity to 27MHz FWHM

-Signal-to-background ratio > 50

Entangling Atoms Using Telecom Photons

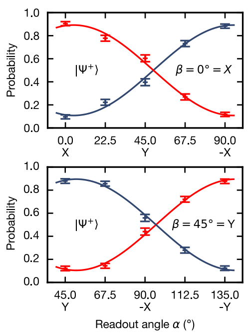


-Projection measurement of the photons onto entangled two-photon Bell-state

-Indistinguishable photons in spatial, temporal and spectral degree of freedom

-Visibility $V_{two\text{-}photon}$: 0.95

-Limited by experimental imperfections, eg., imperfect time overlap and by double excitations events



-L = L_1+ L_2= 3 km + 3 km

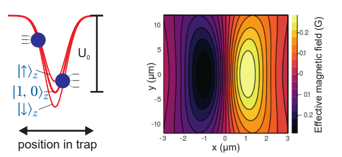
-Back propagation of hearlding signal implemented by additional waiting times

-Average visibility V_{A1A2} : 0.804(20) and 0.784(23) for $|\Psi^-\rangle$and $|\Psi^+\rangle$ respectively

-Extracted CHSH S value of 2.244(63) violates the limit of S = 2 with 3.9σ

Outlook

• Decoherence Mechanisms

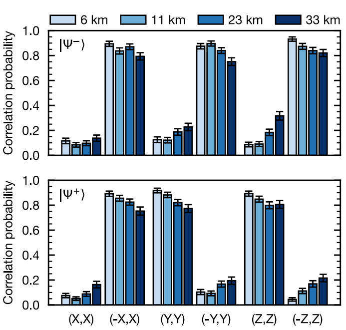


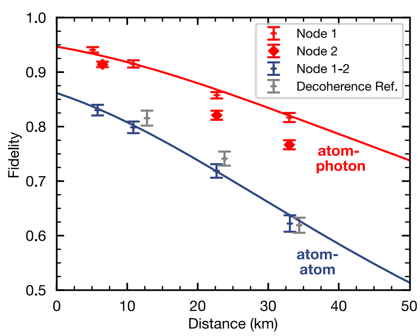
- Circular polarisation of ODT
- Longitudinal polarisation components due to tight focusing of ODT (2 µm)
- External magnetic fields stabilised to 0.5 mG

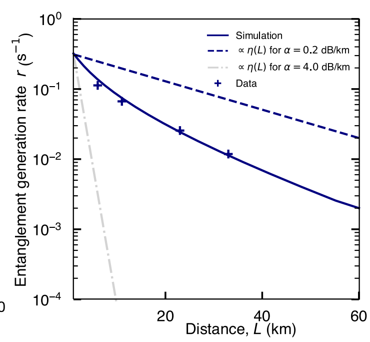
• Improving Coherence Time

- Standing wave dipole trap
- Coherently transfer the qubit to magnetic-field insensitive qubit basis [3]
- Strong guiding field along z-axis to suppress field fluctuations in x and y-axis
- Raman sideband cooling

Atom-Atom Entanglement over Long Fiber Links







-Measured 6 setting along three bases X, Y and Z

-Fidelity estimation includes m_F = 0 substate and is given by $\mathcal{F} = \frac{1}{9} + \frac{8}{9}E'$ where E' is the average contrast given by $E' = (E_X + E_Y + E_Z)/3$

-Success probability is 3.66 x 10^{-6} and 1.22 x 10^{-6} for the shortest and the longest link

-Event rate is 1/9 and 1/85 events/sec for the shortest and the longest link

-Memory decoherence is responsible for the loss in the fidelity for long fibre links

Collaborations

Universität des Saarlandes — Group : Ch. Becher

Max-Planck-Institut für Quantenoptik — Group : G. Rempe

References

[1] T. van Leent et al., Nature 607, 69–73 (2022)

[2] T. van Leent et al., Phys. Rev. Lett 124, 010510 (2020)

[3] M. Körber et al., Nat. Photonics 12, 18-21 (2018)

[4] W. Zhang et al., Nature 607, 687–691 (2022)