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QUANTUM INTERNET ALLIANCE

D1.2 Heralded entanglement between two remote atoms

Document History

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1. Abstract

Entanglement of remote qubits is a central resource for quantum internet protocols. In contrast to monolithic systems, the network architecture offers intrinsically a scalability as it is made of modular blocks that can be combined in a priori limitless numbers. We demonstrate here the potential of such a modular approach. We connect to qubit modules via a 60m-long optical fiber. An ancillary photon is successively reflected on each module to mediate quantum interaction between modules. We show the creation of the four Bell states of these remote qubit in a heralded fashion and demonstrate the realization of a nonlocal quantum-logic gate. Thanks to this modular approach, this protocol can be extended to more qubits in a straightforward way. Those results have led to a publication in peer-reviewed journal [1].

2. Keyword list

Cavity quantum electrodynamics, single photon, hybrid entanglement, quantum gate

3. Acronyms & Abbreviations

DoA	Description of Action
EC	European Commission
WP	Work Package
CQED	Cavity quantum electrodynamics

4. Introduction

Entanglement is at the heart of most quantum information tasks. It is basically the fuel of the most fundamental operations, enabling processing via remote quantum gate or communication via teleportation. However, the full potential of quantum information relies on the scalability i.e. the increase of the number of qubits in play. To this endeavor it is necessary developed systems that are scalable by design. In a network architecture, qubit modules are connected together by quantum links and, ideally, this network can be expended to an almost unlimited number of qubits by simply repeating this pattern.

This approach is particularly interesting when spatial size of the network goes beyond the microscopic scale e.g. when the space available in a cryostat or vacuum chamber is not enough, then optical fibers with photons can be used as quantum links to connect the qubits. Cavity quantum electrodynamics in the optical domain is particularly powerful in this scenario.

Here we show a nonlocal quantum logic gate between two remote matter qubits connected by an optical fiber. Beyond straightforward applications like the generation of Bell states, our system constitutes the elementary building block of distributed quantum computing over a scalable network.

5. Protocol and setup

The overall protocol relies on a mechanism introduced by Duan and Kimble in 2005 where the phase of a photon can be modified while reflecting on a cavity depending on the state of an atom coupled to the cavity. Here this mechanism is used twice as a photon ancillary reflects successively on two cavities. The first reflection is equivalent to a control phase gate performed between two qubits, the photon and the atom *a*. Indeed, if the atom is in the state $|\uparrow_z\rangle$ and the input photon cirularly polarized $|R\rangle$ there is no phase flip whereas for any other combination of input states, there is a change by π of the phase. By controlling the input states, any entangled state can be created. Similarly, with the second reflection, the same logic gate is applied between the second atom and the photon resulting in a tri-partite entangled state. The measurement of the photon will project the remaining atomic qubit states. The final detection of the ancillary photon actually serves two purposes. First it heralds the success of the two intermediate gates, second it gives information on the projected state. This information is used for the feedback on the atomic states (very analogous to a teleportation protocol). Indeed, from the polarization results, one can apply the appropriate feedback to the atomic system in order get a deterministic unitary operation on the two atoms regardless of the polarization measurement results; I our case we perform a local rotation of the first atom. The overall protocol performs a control-NOT gate with atom *a*, the control qubit, and atom *b*, the target qubit. Eventually we perform the following transformation

$$|\uparrow_z\rangle|\uparrow_x\rangle \rightarrow |\uparrow_z\rangle|\uparrow_x\rangle,$$
$$|\uparrow_z\rangle|\downarrow_x\rangle \rightarrow |\uparrow_z\rangle|\downarrow_x\rangle,$$
$$|\downarrow_z\rangle|\uparrow_x\rangle \rightarrow |\downarrow_z\rangle|\downarrow_x\rangle,$$
$$|\downarrow_z\rangle|\downarrow_x\rangle \rightarrow |\downarrow_z\rangle|\uparrow_x\rangle.$$

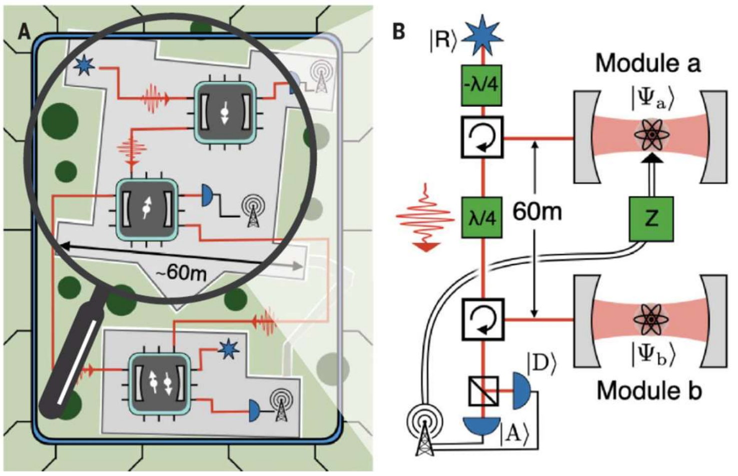

Figure 1 Experimental Setup. (left) vision of a network of quantum modules connected by optical fibres. (right) experimental implementation with two cavities each containing a single atom.

Our setup is made of two identical modules: single ^{87}Rb atoms trapped in high finesse (60000) optical cavities. The qubits are encoded in the atoms on the ground states $|\uparrow_z\rangle = |5^2S_{1/2}, F = 2, m_f = 2\,\rangle$ and $|\uparrow_z\rangle = |5^2S_{1/2}, F = 1, m_f = 1\,\rangle$. The cavity is resonant with the atomic transition $|\uparrow_z\rangle \leftrightarrow |e\rangle = |5^2P_{3/2}, F = 3, m_f = 3\,\rangle$. As an ancillary photon, we use a weak coherent state of average photon number $n = 0.07$. The two cavities are connected by a 60m-long optical fiber. The local rotation of the atomic qubits, preparation, feedback, are performed by stimulated Raman transitions. The state of the photonic qubit is measured with the common combination of wave-plates, polarizing beam-splitter and single photon detectors. The atomic states are measured by fluorescence state detection (relying on the circular transition of F=3 on the D2 line). Each module is run independently by two separated FPGA in each lab and triggered/clocked by a synchronization channel connecting the two labs.

6. Results

In order to characterize the quantum logic gate, two types of measurement are necessary. First, the truth table, analog to a classical gate, gives the classical correlations. The gate is probed with classical bits, in the sense that the input qubits are either 0 or 1 and not in a superposition state. The results of the truth table are plotted on the figure 2. The obtained average fidelity of the truth table is 85%. Second, in order to verify that the gate also works in the quantum regime we need to measure some quantum correlations. Typically this is characterized by the generation of entanglement while the input state is a separable state. For a CNOT gate one obtains the generation of Bell states by probing the gate with an input control qubit in a superposition state. Figure 3 shows the summary table of the different fidelities for the 4 Bell states. On the bottom part of the figure, we plot the density matrices. We have reached an average fidelity of the Bell states of 77%.

Various mechanisms contribute to the non-perfect fidelity of our gate: the use of a coherent state (instead of a true single photon), the state preparation and measurement of our atomic qubits, the polarization control, the spatial mode matching of the cavities with the fibers. All those contributions are individually small in the order of 2-4% but of course accumulate. They are not fundamental limitations though and can in principle be improved: with more accurate tuning, additional active stabilizations, better optical design optimized for this specific application…

The success rate of the gate is mainly limited by two factors. The main one is the fact we use a weak coherent state as a single photon source. This is equivalent to have more than 90% optical losses. The second contribution comes from the optical losses of the cavities and the various optical components constituting the quantum link. However the heralding of the gate success mitigates the effect of those losses. In a computation scenario, the absence of the herald would abort the computation but prevent any corruption of the result.

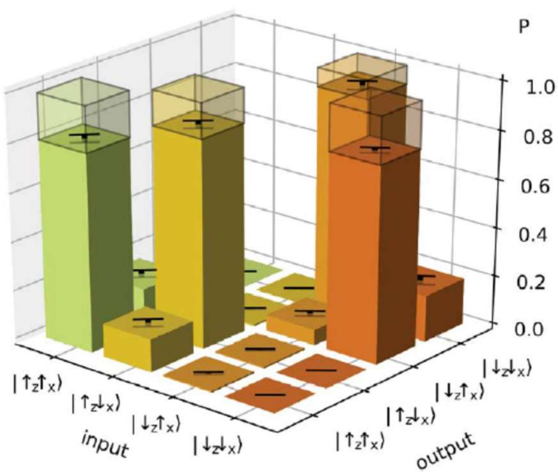

Figure 2 Truth table of the CNOT gate. Classical correlations measured by probing the gate with the different combination of qubits in a ‘‘classical’’ state. The first qubit control the second one: In the up state, the second qubit remains unchanged whereas the down state the second qubit is flipped.

Input state	Output state	Fidelity
$\lvert\uparrow_x\uparrow_x\rangle$	$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\uparrow_x\rangle + \lvert\downarrow_z\downarrow_x\rangle) = \lvert\Phi^+\rangle$	$(78.8 \pm 2.0)\%$
$\lvert\uparrow_x\downarrow_x\rangle$	$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\downarrow_x\rangle + \lvert\downarrow_z\uparrow_x\rangle) = \lvert\Psi^+\rangle$	$(75.1 \pm 2.0)\%$
$\lvert\downarrow_x\uparrow_x\rangle$	$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\uparrow_x\rangle - \lvert\downarrow_z\downarrow_x\rangle) = \lvert\Phi^-\rangle$	$(76.8 \pm 2.0)\%$
$\lvert\downarrow_x\downarrow_x\rangle$	$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\downarrow_x\rangle - \lvert\downarrow_z\uparrow_x\rangle) = \lvert\Psi^-\rangle$	$(75.8 \pm 2.0)\%$

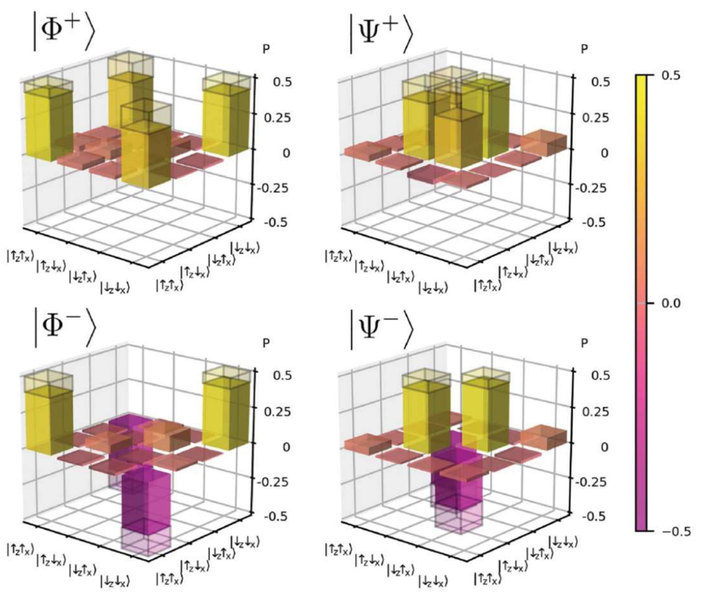

Figure 3 Bell states. Experimental results of the Bell states generation. Fidelity and reconstructed density matrices. The 4 Bell states are obtained by the choice of the input states.

7. Conclusion

In conclusion, we have realized a nonlocal CNOT gate between remote atomic qubits connected by a photonic channel. The success of the gate is heralded, an important feature for quantum information protocols. Beyond the possibility of generating entanglement, this shows the relevance and scalability of distributed quantum computing in a network where quantum modules (end nodes) are connected by optical fibers. Last but not least, our protocol is in principle applicable to many other cavity-QED-based platforms such as quantum dots, impurities-vacancies in diamond or ions.

8. References

[1] Severin Daiss, Stefan Langenfeld, Stephan Welte, Emanuele Distante, Philip Thomas, Lukas Hartung, Olivier Morin, Gerhard Rempe, A quantum-logic gate between distant quantum-network, *Science* **371**, 614-617 (2021)