QUANTUM INTERNET ALLIANCE

D1.1 Hybrid entanglement between a trapped-atom qubit and a continuous-variable light state

Document History

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Index

1. Abstract

Since the beginning of quantum information, two pathways have been followed: “continuous variables” and “discrete variables”. Only recently have efforts been made to combine these two approaches and design protocols that take the best of both worlds. Currently, most end nodes rely on light-matter interfaces. However, the combination of atomic systems with continuous variables is so far almost non-existent. This deliverable intends to make a significant step towards creating such interfaces, more precisely, by experimentally realizing entanglement between a single atom and a continuous-variable light states. In addition, it enables the identification of the main weaknesses of such approaches and therefore the challenges that need to be addressed in the future in order to use them in realistic protocols. In the present report we show that we successfully reached our goal: we demonstrated the generation of this hybrid entanglement, characterized it quantitatively and also used it as a primary resource for various applications in quantum information. Those results have led to two publications in peer-reviewed journals [1,2].

2. Keyword list

Cavity quantum electrodynamics, Schrödinger cat state, single photon, hybrid entanglement, quantum gate

3. Acronyms & Abbreviations

DoA	Description of Action
EC	European Commission
WP	Work Package

4. Introduction

The wave-particle duality of light was the starting point of the quantum theory which unified the two points of view via a dedicated formalism. However, it remains convenient to describe light fields with either the "wave" or "particle" point of view. Those two descriptions have led to the two so-called continuous- and discrete-variables approaches in quantum information. For discrete variables, a photonic qubit is encoded in a single photon, whereas for continuous variables approaches, the qubit is encoded in phase space (often represented by the Wigner function). Within just the past decade, some new protocols have proposed to combine both encodings. The main interest of such a strategy is to combine the advantages of each approach.

In continuous-variable quantum information, the coherent states $|\alpha\rangle$ and $|-\alpha\rangle$ can constitute a qubit basis as long as they are orthogonal. This is effectively achieved for a sufficiently large amplitude as the overlap is equal to $|\langle\alpha|-\alpha\rangle|^2 = \exp(-4|\alpha|^2)$. Over the years, superpositions of two coherent states with opposite phases have been called "Schrödinger cat states". This labelling refers to the famous article by Erwin Schrödinger. As a coherent state is considered a "classical" state, it makes an analogy with the cat that plays the role of the classical object in the Gedankenexperiment proposed by E. Schrödinger. Therefore, coherent states with opposite phases correspond to the "orthogonal" states of the cat, namely, dead or alive. Two superpositions are particularly interesting: $|\mathrm{cat}_\pm\rangle = N(|\alpha\rangle \pm |-\alpha\rangle)$. Indeed, they are composed by photon numbers states of the same parity. The "even" cat state $|\mathrm{cat}_+\rangle$ is a superposition of even Fock states and the "odd" cat state $|\mathrm{cat}_-\rangle$ is a superposition of odd Fock states.

So far, atomic systems have only been interfaced with discrete-variable photonic qubits. Therefore, an atomic interface for continuous-variable photonic qubits is definitely a missing component for the development of hybrid architectures. In the present deliverable we use a cavity quantum electrodynamic effect to entangle a single-atom state with a continuous-variable light state. We also show that these states constitute the starting point for multiple applications: continuous-variable quantum state engineering, a hybrid quantum gate, and single photon generation.

5. Hybrid entanglement generation

5.1. Protocol

Here, we use a fundamental effect of cavity quantum electrodynamics. Starting from an atom in a high finesse optical cavity, we use three levels of the atom, two ground states and one excited state. The cavity is resonant with only one of the two optical transitions of the atom. In this configuration, two situations are possible: either the atom is in the ground state $|\downarrow\rangle$ and is not coupled to the cavity, or is in the state $|\uparrow\rangle$ and is coupled to the cavity. This latter case leads to the effect called normal-mode splitting; the energy eigenstate of the system atom+cavity is split. As a result, an impinged light field resonant with the cavity and the atom, separately, is not resonant with the global system and simply gets reflected by the input mirror, remaining unchanged. In contrast, when the atom is in the state $|\downarrow\rangle$, it is not coupled to the cavity. In this case, an impinged light field is resonant with the cavity and acquires a π phase shift after reflection. This effect can be summarized as

$$|\uparrow\rangle|+\alpha\rangle \longrightarrow |\uparrow\rangle|+\alpha\rangle \ ,$$

$$|\downarrow\rangle|+\alpha\rangle \longrightarrow |\downarrow\rangle|-\alpha\rangle \ .$$

Given this transformation, it is now clear that starting with the atom in a superposition of the two states $|\uparrow\rangle$ and $|\downarrow\rangle$, a light field interacting with the system will end in an entangled state between the light and the atomic states.

Starting from the state $|\downarrow\rangle$, a $\pi/2$ rotation brings the atom into the superposition $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$. Hence, after reflection of a coherent state $|\alpha\rangle$ off the cavity, the entangled state $(|\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle)/\sqrt{2}$ is generated. A second rotation of the atom leads to the state $(|\uparrow\rangle|\mathrm{cat}_{+}\rangle + |\downarrow\rangle|\mathrm{cat}_{-}\rangle)/\sqrt{2}$. As we will show, this entangled state, and more generally the interaction mechanism between an external light field and the cavity QED system, offers multiple possibilities. We have investigated several of them: the generation of non-Gaussian states, atom-light entanglement, and an atom-light quantum gate. This is further detailed in the Results section.

5.2. Experimental setup

Our experimental setup is shown in Figure 1 and comprises a single ^{87}Rb atom trapped in a high finesse optical cavity. The atom preparation and position is monitored by a highly sensitive camera by collecting fluorescence light. The atom state is initialized by optical pumping into the state $|\uparrow\rangle = |F=2, m_f=2\rangle$. Afterwards, a pair of Raman lasers allows for coherent transfer to $|\downarrow\rangle = |F=1, m_f=1\rangle$. The light field after the interaction is characterized using homodyne detection, where the generated light is mixed with a strong local oscillator (LO) on a beam splitter. The marginal distributions of the Wigner function can be inferred from a difference in the photocurrent of two photodiodes in the beam splitter output modes. To prevent LO light from interacting with the intra-cavity atom, an optical isolator is placed between the cavity and the homodyne setup. However, our protocol involves a light state and the atomic state. The latter needs to be measured too. This is done by using light resonant with the transition $|\uparrow\rangle \leftrightarrow |e\rangle$, with excited state $|e\rangle = |F'=3, m_f=3\rangle$, such that fluorescence state detection can be performed. As shown in Figure 1, the path for the light from the state detection is steered to a single photon detector via an acousto-optic deflector (AOD).

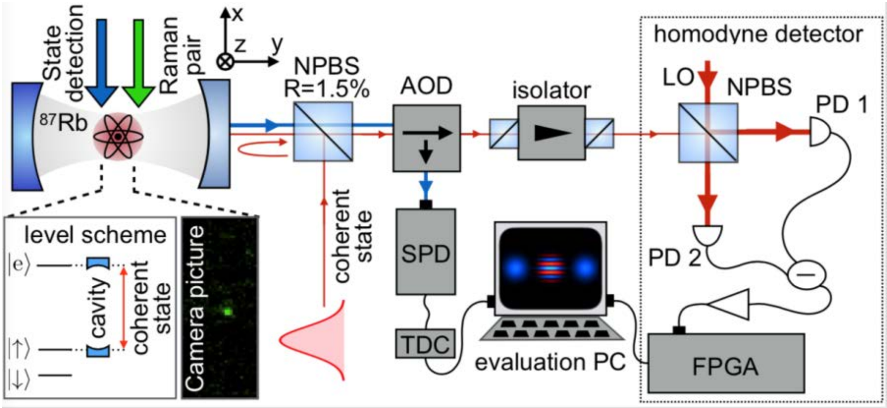

Figure 1 Experimental Setup. The optical cavity (left) contains a single atom that is controlled and read out with laser beams. Coherent states are reflected from the cavity and propagate to a homodyne detection setup (right). The inset on the left shows a simplified level scheme of the atoms. More technical details can be found in [1].

6. Results

6.1. Cat states

The optical cat states are obtained by a projective measurement. Starting from the entangled state $(|\uparrow\rangle|\mathrm{cat}_+\rangle + |\downarrow\rangle|\mathrm{cat}_-\rangle)/\sqrt{2}$, the measurement of the atomic state projects the light state onto one of the two cat states. The result of the measurement heralds the corresponding photon number parity. Post-selection of the data on the respective outcomes of the measurements of the atomic state thus allows us to distinguish between the even and the odd cat state. For the characterization of the respective states, the Wigner function is reconstructed by means of homodyne tomography. Ideally, this Wigner function of an odd and an even cat state shows in phase space two opposite Gaussian distributions with strong interference fringes in between. The phase of the interference pattern depends on the parity of the respective cat state. The produced states are so-called non-Gaussian states and feature regions in the Wigner function with negative values. In the experimental data we indeed observed such negative values in the Wigner function, confirming the quantum nature of the produced states as shown in Figure 2. The different phases of the interference fringes are observable as well as a significant negativity of the Wigner function in the case

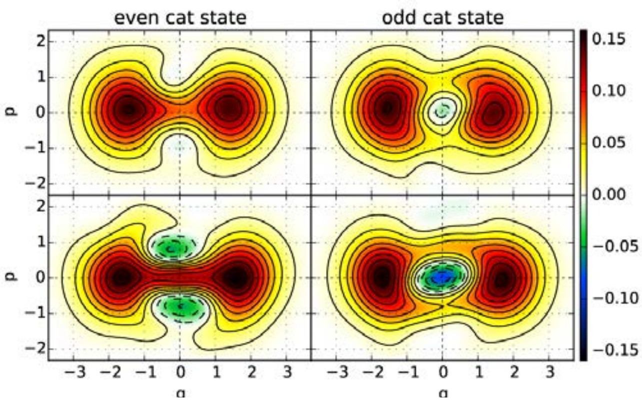

Figure 2 Generation of even and odd cat states. The top row shows the even and the odd cat states as they were measured in the experiment. The two cat states correspond to a measurement of the atom in the state $|\uparrow\rangle$ or $|\downarrow\rangle$, respectively. The bottom row shows the respective Wigner functions corrected for propagation and detections losses of the propagating cat states.

of an odd cat state. The experimentally obtained data can be corrected for propagation and detection losses of the light. With this technique, it is possible to infer the shape of the respective Wigner functions directly after the cat state has been generated. The respective plots are shown in the bottom row of Figure 2. The negativity is much more pronounced as the interference stripes are not smeared out as much as in the data shown in the upper row.

6.2. Hybrid entanglement

According to the protocol, the state $(|\uparrow\rangle|+\alpha\rangle+|\downarrow\rangle|-\alpha\rangle)/\sqrt{2}$ is generated after the coherent pulse is reflected from the cavity. It should be pointed out that this entangled state between the atom and the respective coherent state is generated in each single attempt deterministically without any need for post-selection on the data. In addition, although the generation of cat states presented in the previous section seems to confirm the presence of hybrid entanglement, it is not sufficient, as it only proves the classical part of the correlation between the light and the atom states. To verify the generation of entanglement, tomography was performed, and the atomic qubit was measured in three different bases (*x*, *y* and *z*). Each measurement results in a different corresponding photonic state. From the measurements, the joint Wigner functions (shown in Figure 3 on the right) as well as the full density matrix of the atom-light state can be deduced. From this density matrix, an entanglement negativity $N = 0.057(5)$ is extracted, where any value of $N > 0$ demonstrates entanglement. As explained in the introduction, there is a strong analogy with Schrödinger's Gedankenexperiment where a cat in a box eventually becomes entangled with a decaying atom. In our experiment, the cat is replaced by the optical light field, which can in principle be increased to contain more photons in order to generate an entangled state between a microscopic atom and a macroscopic light state. Experimentally, as for the previous experiment, the optical losses smear out the observed interference fringes as α is increased. In our implementation, the optical pulse contained up to four photons on average.

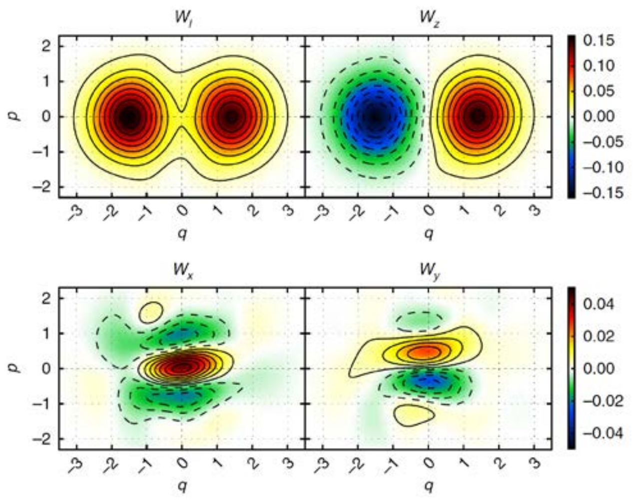

Figure 3 Entanglement between atom and cat states. The four joint Wigner functions are shown for different measurement bases of the atomic state. From these measurements, the density matrix of the atom-light state can be inferred.

6.3. Hybrid gate

The strong interaction between the atom and the incident light allows not only for the creation of non-classical light but can also be employed to perform a hybrid quantum gate between a continuous variable light state in the basis $|\alpha\rangle$ and $|-\alpha\rangle$ and the atomic spin $|\uparrow\rangle$ and $|\downarrow\rangle$. Ideally, the truth table in the combination of these bases after an interaction is then given by

$$\begin{aligned} |\uparrow\rangle|+\alpha\rangle &\longrightarrow |\uparrow\rangle|+\alpha\rangle, \\ |\uparrow\rangle|-\alpha\rangle &\longrightarrow |\uparrow\rangle|-\alpha\rangle, \\ |\downarrow\rangle|+\alpha\rangle &\longrightarrow |\downarrow\rangle|-\alpha\rangle, \\ |\downarrow\rangle|-\alpha\rangle &\longrightarrow |\downarrow\rangle|+\alpha\rangle, \end{aligned}$$

and the gate acts as a Controlled-NOT gate on these basis states. We measured this truth table, where the optical phase is again detected with our homodyne setup. The resulting overlap with the ideally expected result is around 86%. This value is limited by phase noise from cavity and laser fluctuations that broaden the Wigner function of the reflected light and thus diminish the overlap with an ideal Wigner function for $|\alpha\rangle$ or $|-\alpha\rangle$. If we discriminate between these two basis states just by the sign of the q-quadrature of the Wigner function, the fidelity increases to 96%.

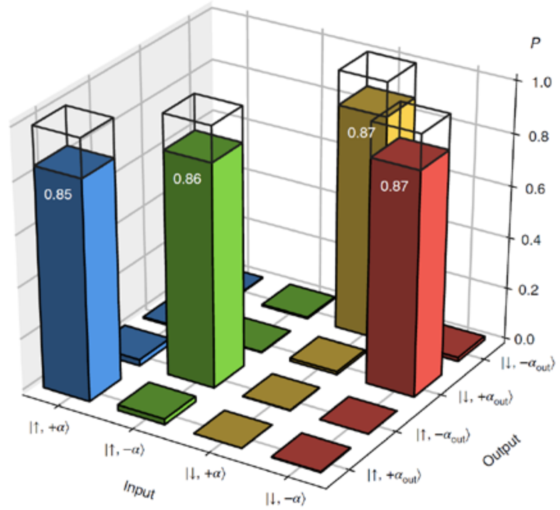

Figure 2 Truth table of the atom-cat gate. The data corresponds to a CNOT gate, where the state of the atom controls the optical qubit.

6.4. Single photon distillation

Even and odd cat states $|\mathrm{cat}_{\pm}\rangle = N(|\alpha\rangle \pm |-\alpha\rangle)$ only have photon contributions of either even or odd parity. Thus, our protocol effectively constitutes a parity measurement on the light that is reflected from the cavity. This can be used to remove undesired Fock-state contributions from incident light pulses, as long as they have a different parity than the target state. An important application of this is the ability to clean up light from various imperfect single-photon sources and remove the detrimental two-photon component from it. This principle has been tested in the experiment by using weak coherent pulses with $|\alpha| \ll 1$. Such pulses are dominated by their vacuum contribution and still have non-negligible two-photon terms. Using our protocol and correcting for known effective losses distilled this input into a single-photon state having fidelity of up to 66%. We show both the reconstructed Wigner function (see Figure 5) and cross-correlation measurements of down to $g^{(2)}(0) = 0.045(6)$. These measurements independently confirm the single-photon character of the resulting optical state. A theoretical analysis based on the input-output formalism shows that the main limitation in the purity of the produced state comes from our cavity QED parameters and could be vastly improved with state-of-the-art fiber cavity systems.

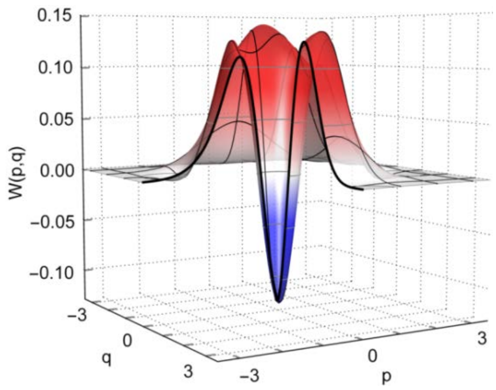

Figure 5. Wigner function of the distilled single-photon state.

7. Conclusion

We have shown the first generation of entanglement between a single atom and a continuous-variable light state. This hybrid entanglement is a fantastic resource for quantum information based on hybrid architectures and beyond. It can be used to deterministically generate coherent state superpositions, a fundamental resource in continuous-variable quantum information processing; to build a hybrid gate; and also to generate single photons in a new way. The main challenge for future use of this resource is the optical losses; a cat state cannot be propagated over a-long distance fiber connection. However, except for dual rail qubits, this is an issue for most qubit encodings, and strategies exist to go around this problem.

8. References

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