LETTER

doi:10.1038/nature18592

A photon–photon quantum gate based on a single atom in an optical resonator

Bastian Hacker[1]*, Stephan Welte[1]*, Gerhard Rempe[1] & Stephan Ritter[1]

2017-04-17

Journal club

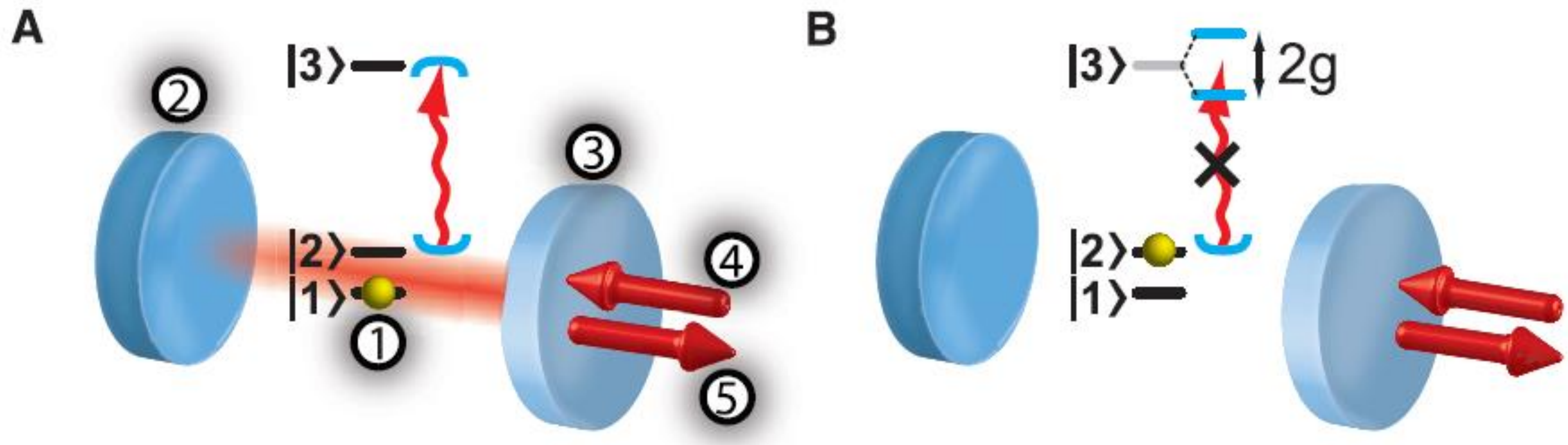
Authors

- G. Rempe
  - Director @ Max Planck Institute of Quantum optics, quantum dynamics
- S. Ritter
  - Scientist @ Max Planck Institute of Quantum optics, quantum dynamics
  - Nondestructive Detection of an Optical Photon , Science (2012)
  - A quantum gate between a flying optical photon and a single trapped atom, Nature (2014)
  - A photon-photon quantum gate based on a single atom in an optical resonator, Nature (2016)

Introduction

- No direct photon-photon interaction
  - Nonlinear medium needed
  - Simultaneous overlap of two photons – locality & causality problem
  - Alternative solution : consecutive interaction followed by state reduction
- Single atom in cavity : strong nonlinearity

Nondestructive Detection of an Optical Photon



- External field couple to cavity only in the case of atom in |1> state
- Two cases differ by overall quantum phase of π
- With initial atomic state with superposition state, the phase precession was measured

Quantum gates

- Single qubit gate
  - Hadamard gate, Pauli gates, phase gates
  - single qubit rotation – Rabi oscillation
- Two qubit gate
  - Controlled-NOT gate (C-NOT)

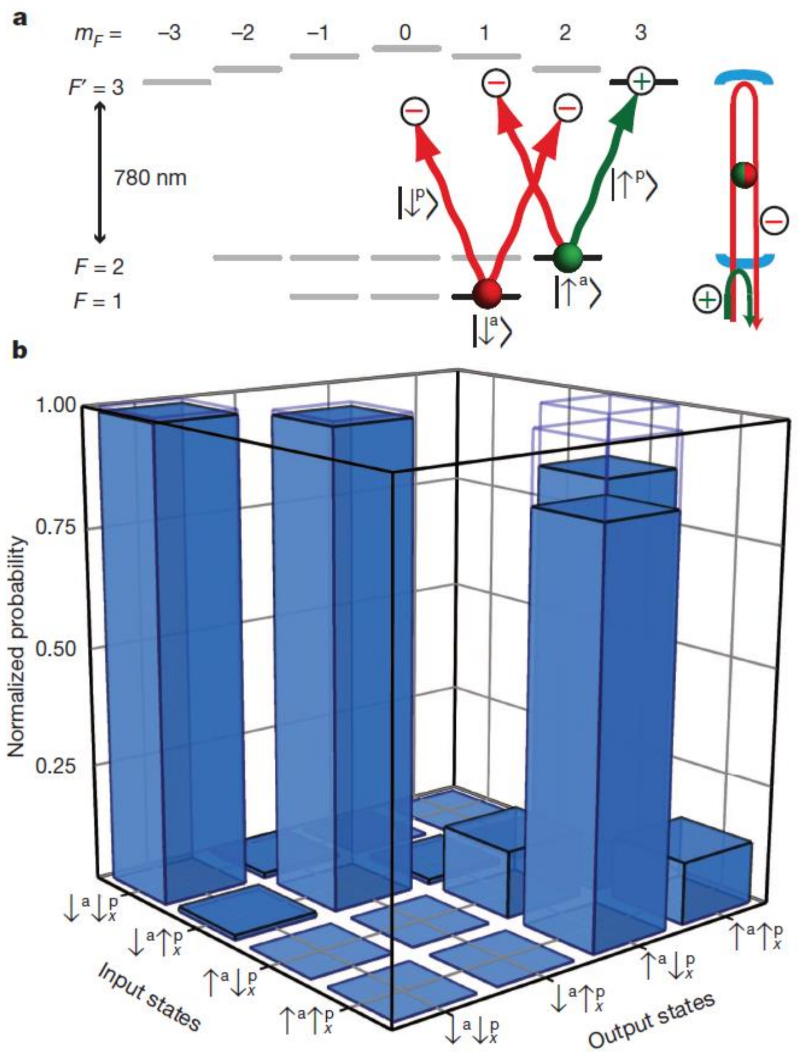
Before		After	
Control	Target	Control	Target
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

$$\mathbf{cNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$\mathbf{cNOT}\ \boldsymbol{\psi} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}\begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \\ \delta \\ \gamma \end{pmatrix}$$

  - Controlled-phase gate or Controlled-Z gate

A quantum gate between a flying optical photon and a single trapped atom



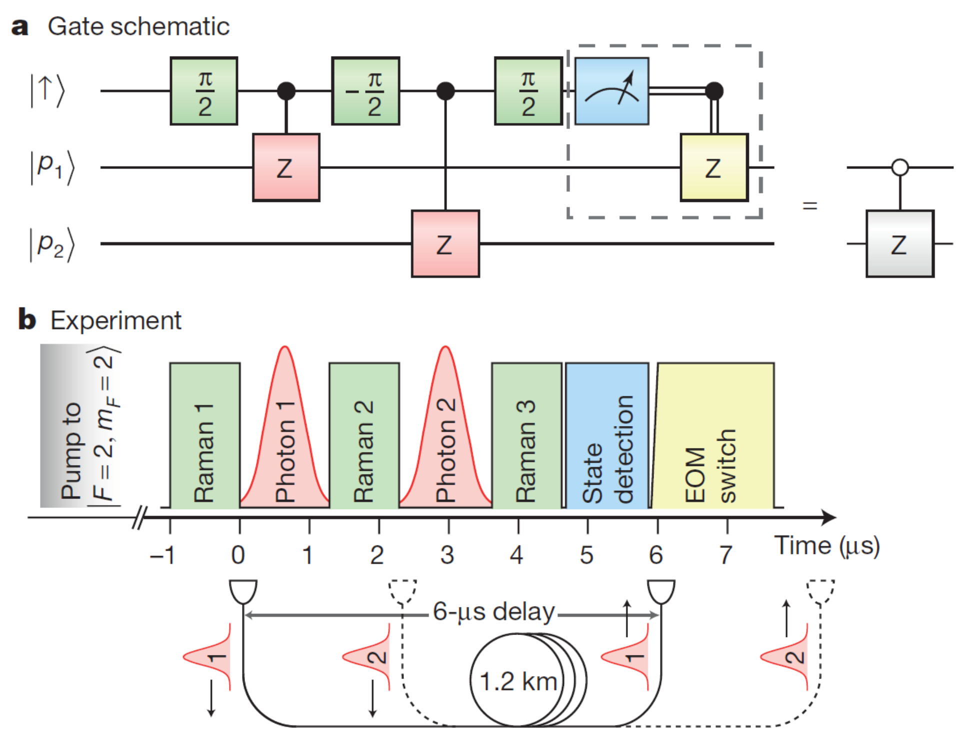
- Photon qubit : polarization (- / +)
- Zeeman splitting allows only + polarization interact with atom-cavity system
- C-phase gate → C-NOT gate (basis rotation)

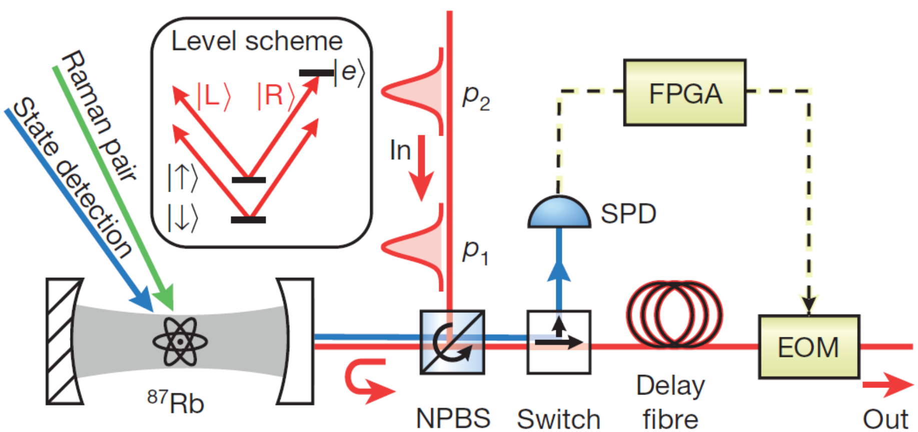
Exp scheme

Atom as an ancillary qubit :

First photon :

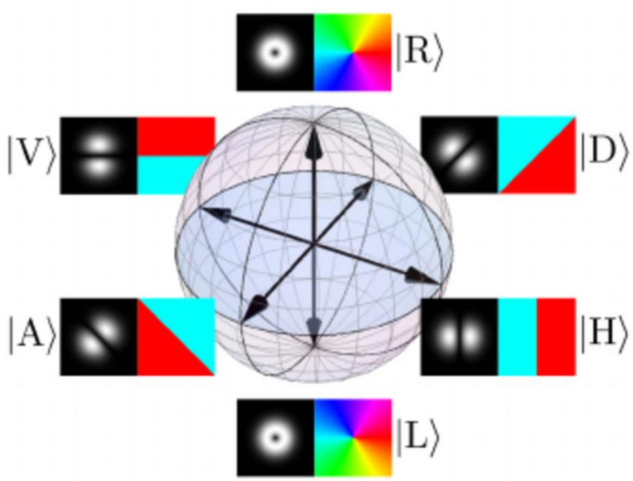
Second photon :

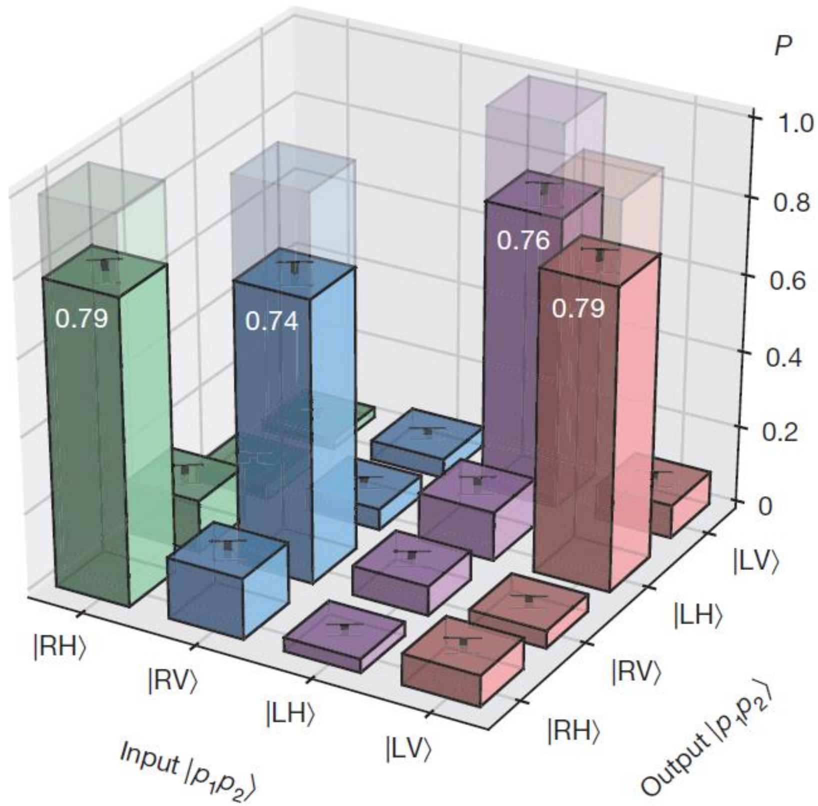




photon-photon C-NOT gate

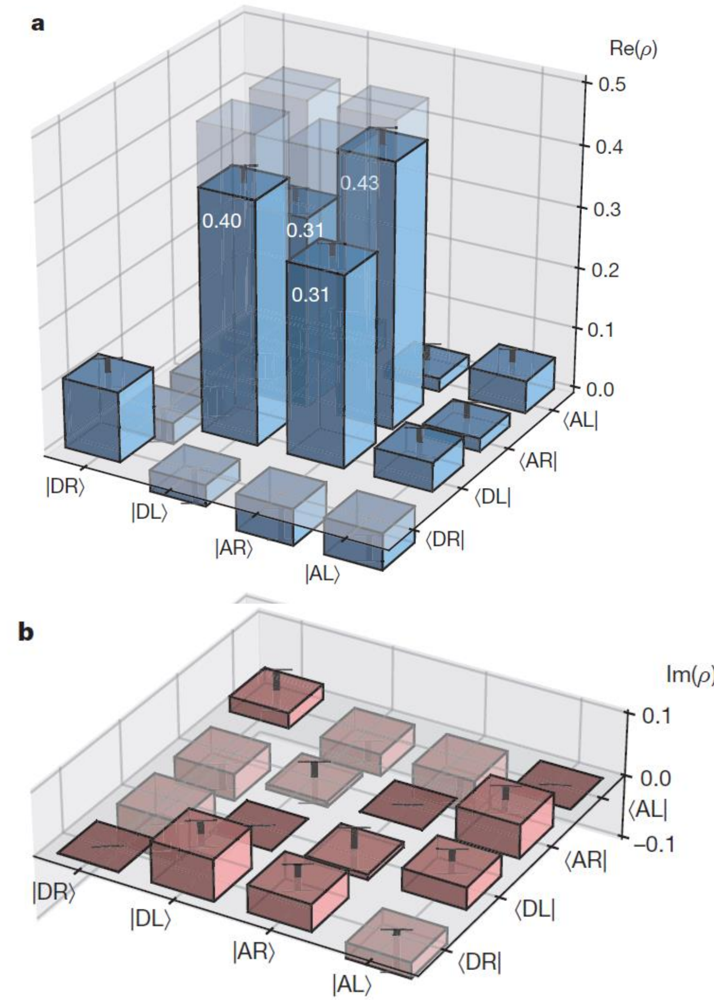
- Basis rotation on second photon → C-Z gate to C-NOT gate
- Gate fidelity : (76.9±1.5)%





Entanglement generation by quantum gate

- Input state : $|DD\rangle$
- Expected output state ;
  $|\Psi_{BELL}\rangle = \frac{1}{\sqrt{2}}(|DL\rangle + |AR\rangle)$
- State Fidelity : (72.9±2.8)%
- Entangling capability :
  $C < -0.242 \pm 0.028$



Discussion

- Average gate fidelity : 76.2±3.6%
- Gate efficiency
  - Fiber loss (T= 40.4%), limited cavity reflectivity (R=67%), optical element loss (T= 81%) → overall 22%
  - Two photons $(22\%)^2 = 4.8\%$
- Gate fidelity
  - Two photon case ($\bar{n} = 0.17$) → reduction 12%
  - Photon bandwidth (limited by delay time) : 6%
  - etc. (cavity characteristic – 5%, atomic state – 6%, other optical element - 2%)

Q&A

- 10p. Why cavity reflectivity is limited? (Jinuk)
  - Not perfectly one-sided cavity – leakage to other side of cavity, finite cooperativity of C=3.3
- Difference between quantum gate vs. classical gate (Daeho)
  - Do not measure qubit state → reversible process (unitary)