Photon-Mediated Quantum Gate between Two Neutral Atoms in an Optical Cavity

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HAN JUN SEOK

Gerhard Rempe

- Honorary Professor at the Technical University of Munich
- Director at Max Planck Institute of Quantum Optics

Research Interests

- Cavity Quantum Electrodynamics
- Quantum Information Processing
- Bose Einstein Condensation
- etc.

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Optical Kaleidoscope Using a Single Atom

P. Horak and H. Ritsch
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

T. Fischer, P. Maunz, T. Puppe, P. W. H. Pinkse, and G. Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
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Submicron Positioning of Single Atoms in a Microcavity

Stefan Nußmann, Markus Hijlkema, Bernhard Weber, Felix Rohde,* Gerhard Rempe, and Axel Kuhn
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
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Interference and dynamics of light from a distance-controlled atom pair in an optical cavity

A. Neuzner, M. Körber, O. Morin, S. Ritter* and G. Rempe

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

Andreas Reiserer[1], Norbert Kalb[1], Gerhard Rempe[1] & Stephan Ritter[1]

LETTERS

A single-photon server with just one atom

MARKUS HIJLKEMA[1], BERNHARD WEBER[1], HOLGER P. SPECHT[1], SIMON C. WEBSTER[1], AXEL KUHN[2] AND GERHARD REMPE[1]*
[1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
[2]Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
*e-mail: gerhard.rempe@mpq.mpg.de

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Feedback on the Motion of a Single Atom in an Optical Cavity

T. Fischer, P. Maunz, P. W. H. Pinkse, T. Puppe, and G. Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
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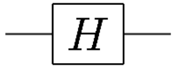
Quantum logic gate and qubit

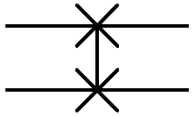
Qubit $|\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}, |\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$ and $|\uparrow\uparrow\rangle = \begin{pmatrix}1\\0\\0\\0\end{pmatrix}, |\uparrow\downarrow\rangle = \begin{pmatrix}0\\1\\0\\0\end{pmatrix}, |\downarrow\uparrow\rangle = \begin{pmatrix}0\\0\\1\\0\end{pmatrix}, |\downarrow\downarrow\rangle = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$

Hadamard Gate



$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$$

SWAP Gate



$$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}$$

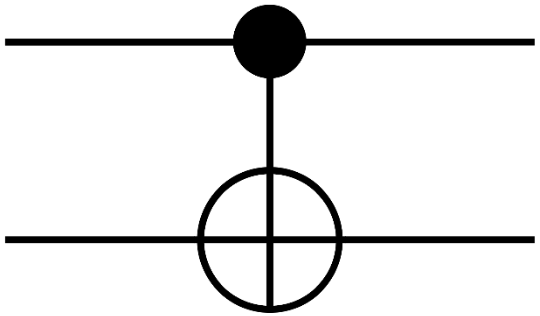
Pauli X-Gate (NOT Gate)

$$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$$

CNOT Gate

Controlled NOT (or X) Gate acts on two qubits

NOT operation executed on second qubit only when first qubit is in $|\downarrow\rangle$



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Qubit

$|1\rangle : |\Psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

$|2\rangle : |\Psi^+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$

$|3\rangle : |\Phi^-\rangle = (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)/\sqrt{2}$

$|4\rangle : |\Phi^+\rangle = (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)/\sqrt{2}$

$\xrightarrow{\text{CNOT}}$

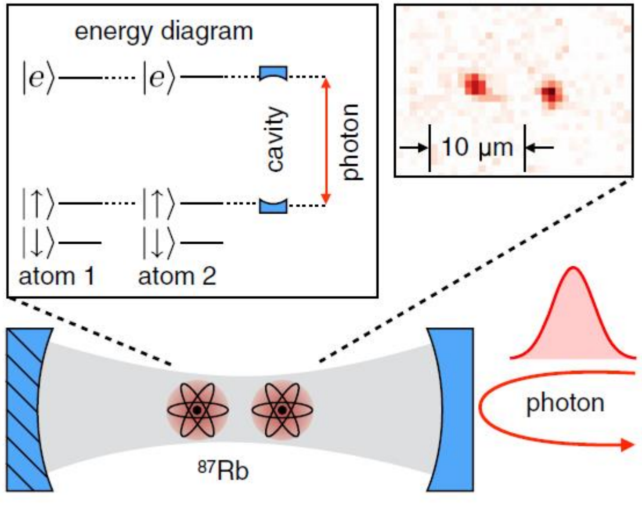
$|\Psi^-\rangle$

$|\Psi^+\rangle$

$|\Phi^+\rangle$

$|\Phi^-\rangle$

Method



Two ^{87}Rb atoms in $2\sim12\mu m$ distance
Weak coherent pulse with $\bar{n} = 0.13$

$|e\rangle$: $5^2P_{3/2}|F' = 3, m_F = 3\rangle$
$|\uparrow\rangle$: $5^2S_{1/2}|F = 2, m_F = 2\rangle$
$|\downarrow\rangle$: $5^2S_{1/2}|F = 3, m_F = 1\rangle$

$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle$ $\quad$ $|\downarrow\uparrow\rangle \rightarrow |\downarrow\uparrow\rangle$

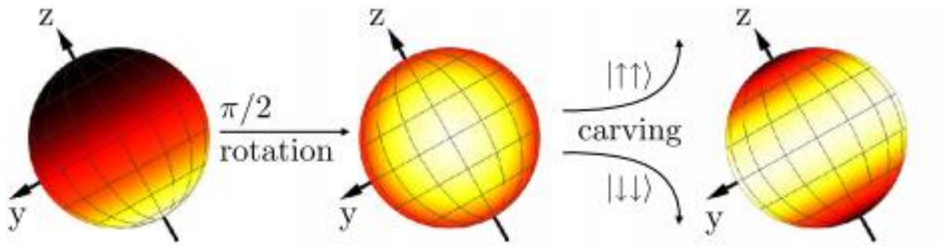
$|\uparrow\downarrow\rangle \rightarrow |\uparrow\downarrow\rangle$ $\quad$ $|\downarrow\downarrow\rangle \rightarrow -|\downarrow\downarrow\rangle$

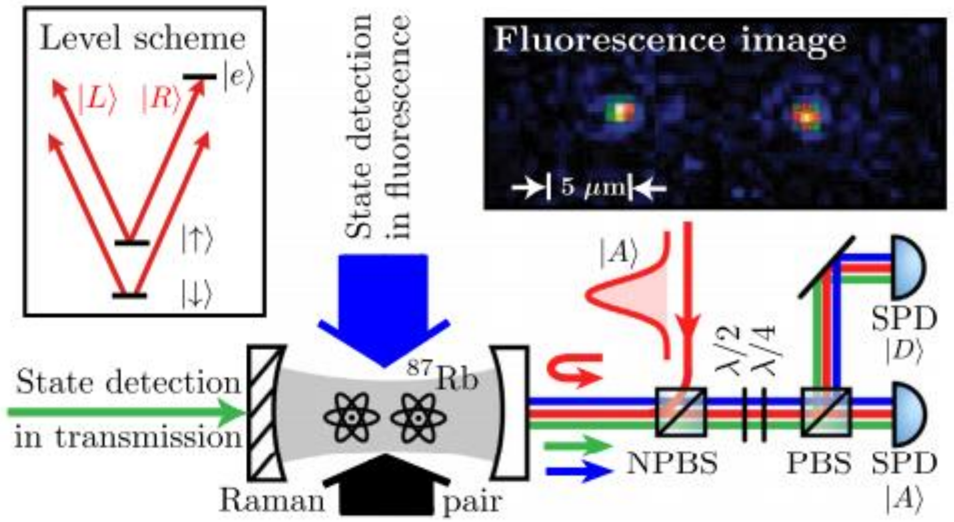
Experimental Setup

- Cavity profile
  - Finesse $F = 6 \times 10^4$
  - Asymmetric cavity: high-reflective mirror reflectivity of 99.9994% and out coupling mirror 99.99%
- $(g, \kappa, \gamma) = 2\pi \times (7.8, 2.5, 3.0) MHz$
- 3D optical lattice with Sisyphus cooling to $100 \mu K$

Preparing States

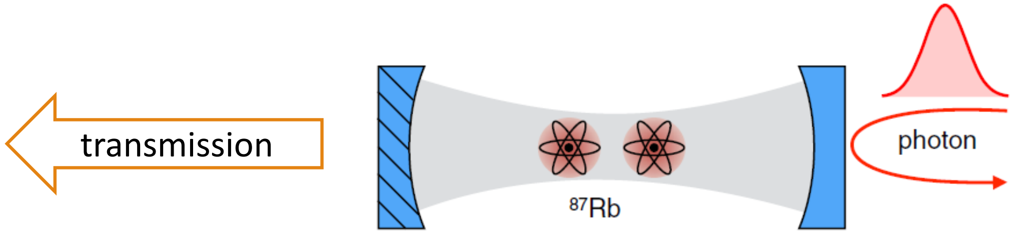
Cavity Carving



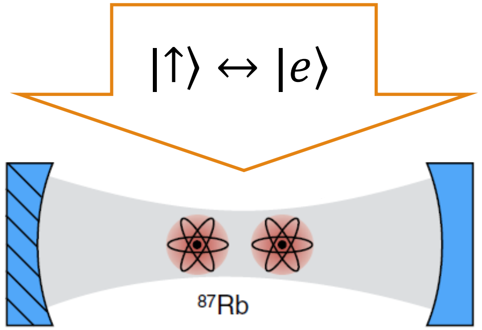


State Detection

1. Measuring transmission through high-reflectivity mirror



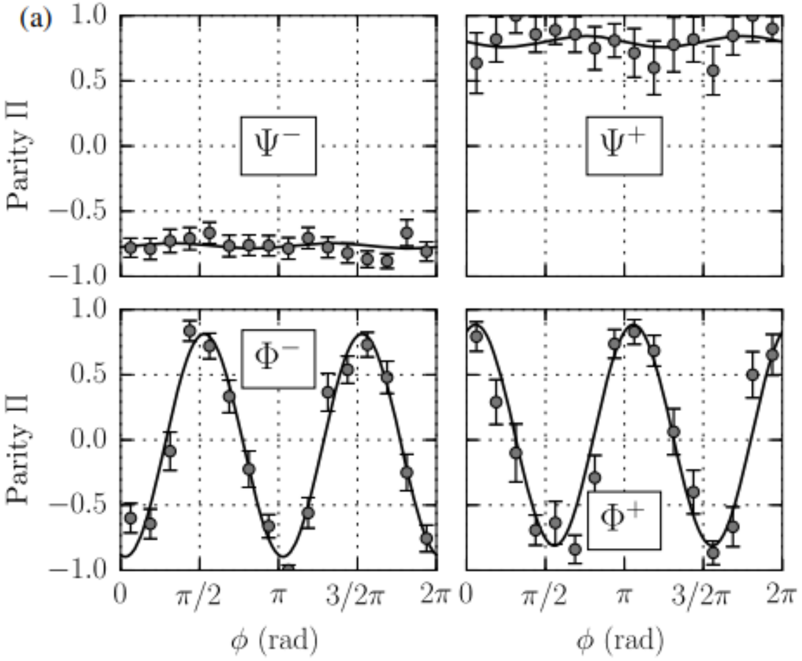
2. Fluorescence



Parity Oscillation

-Rotate state with Raman laser for ϕ and measure probabilities of each states

-Caluclate $\Pi(\phi) = P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - (P_{\uparrow\downarrow} + P_{\downarrow\uparrow})$



-Fidelity
$F = \langle\Psi|\rho|\Psi\rangle$, ρ: measured state density matrix, $|\Psi\rangle$: ideal state

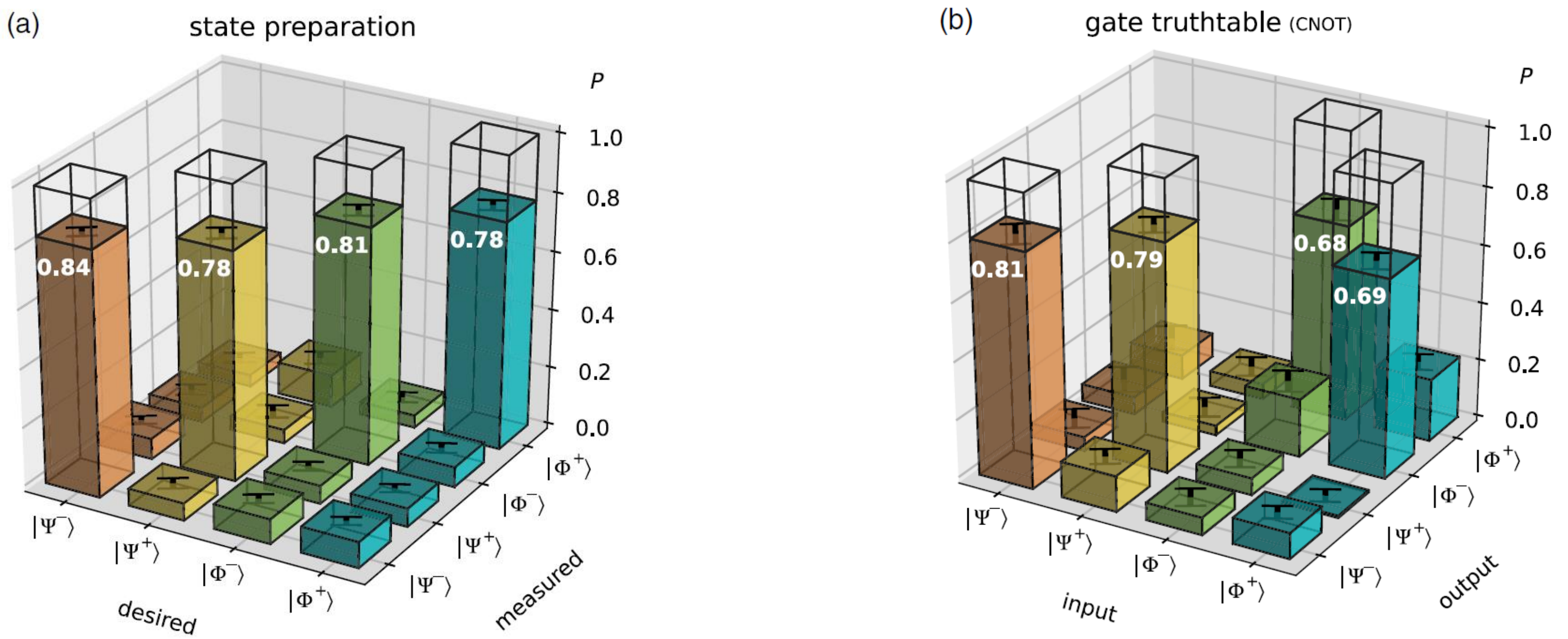
$$F(|\Psi^{\pm}\rangle) = \frac{1}{2}(P_{\uparrow\downarrow} + P_{\downarrow\uparrow}) \pm \mathrm{Re}(\rho_{\uparrow\downarrow,\downarrow\uparrow})$$

$$F(|\Phi^{\pm}\rangle) = \frac{1}{2}(P_{\uparrow\uparrow} + P_{\downarrow\downarrow}) \pm \mathrm{Re}(\rho_{\uparrow\uparrow,\downarrow\downarrow})$$

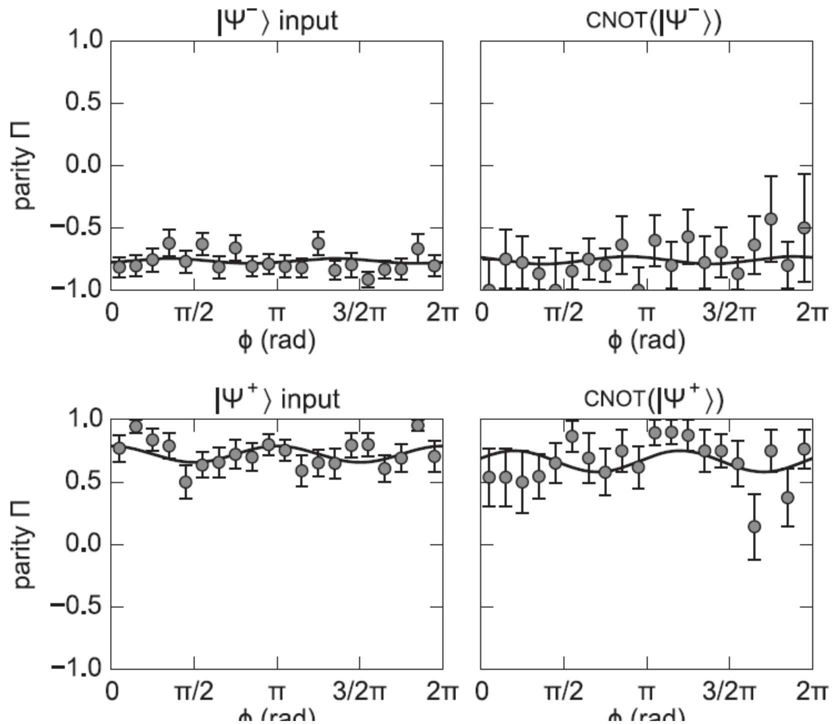
Timing

- π pulse duration $8\mu s$, Gaussian intensity profile with a full width at half maximum of $0.9\mu s$
- Two pulses with $\bar{n} = 0.33$ for state preparation
- Length of 5 and $3\mu s$ for a state detection in fluorescence and transmission.
- Repeat the protocol of length $70\mu s$ at a rate of $1kHz$ with laser cooling intervals of $0.7\mu s$

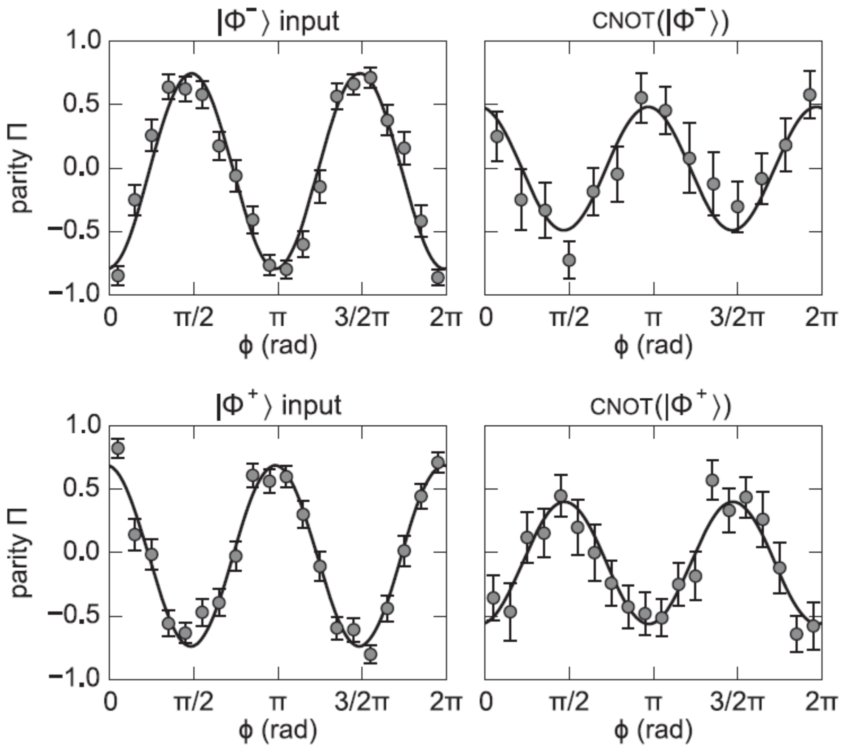
Result


(a)
state preparation
P
1.0
0.8
0.6
0.4
0.2
0.0
0.84
0.78
0.81
0.78
|Ψ⁻⟩
|Ψ⁺⟩
|Φ⁻⟩
|Φ⁺⟩
desired
measured
(b)
gate truthtable (CNOT)
0.81
0.79
0.68
0.69
input
output

Result



|Ψ⁻⟩ input
CNOT(|Ψ⁻⟩)
|Ψ⁺⟩ input
CNOT(|Ψ⁺⟩)
parity Π
ϕ (rad)



|Φ⁻⟩ input
CNOT(|Φ⁻⟩)
|Φ⁺⟩ input
CNOT(|Φ⁺⟩)
parity Π
ϕ (rad)

Errors

TABLE I. Sources of error for the experimental fidelity of the $|\Phi^-\rangle$ state created by the entangling gate operation. Given values are the absolute decrease in fidelity due to each effect if all other influences are kept constant. The effects are not independent, which has to be taken into account if multiple error sources are summed.

Source of error	Fidelity reduction
Finite mode matching	6%
Erroneous state detection	4%
Multiphoton contributions	3%
Photon loss in the cavity	3%
Heralding detector dark counts	2%
Photon polarization inaccuracy	1%
Atomic state preparation	1%
Atomic state dephasing	1%

With single photon source, fidelity can go up to 82% in ideal case