Quantum controlled-Z gate for weakly interacting qubits

Michal Mičuda, Robert Stárek, Ivo Straka, Martina Miková,
Miloslav Dušek, Miroslav Ježek, Radim Filip, and Jaromír Fiurášek

Department of Optics, Palacký University,
17. listopadu 12, 77146 Olomouc, Czech Republic

CZECH SCIENCE FOUNDATION

Outline of the talk

1. Linear optical quantum CZ gate
2. Quantum CZ gate with weak interferometric coupling
3. Experimental setup and results
4. Quantum CZ gate for weakly interacting single atoms, ions, or spins

Quantum CZ gate

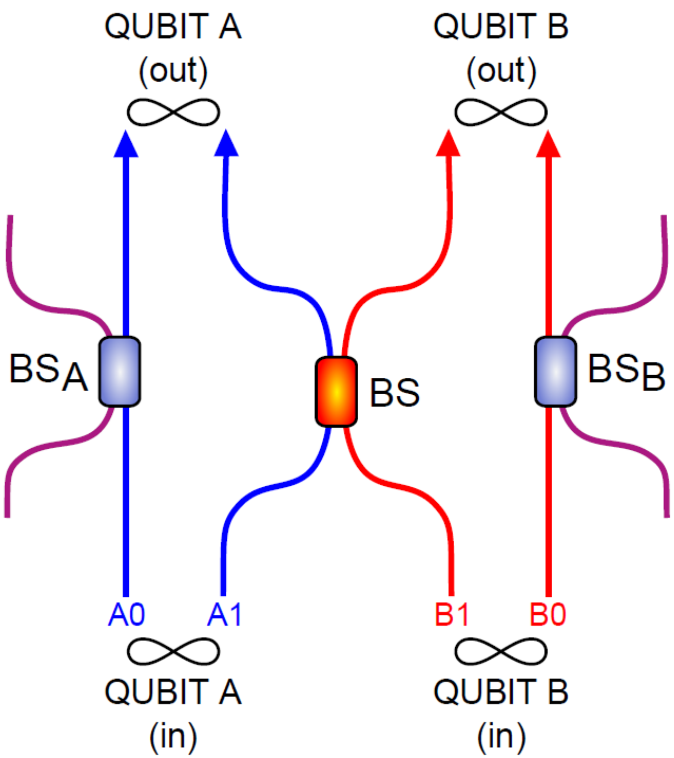
Perfect quantum U-NOT gate would map every input qubit state onto an orthogonal state:

$$\forall|\psi\rangle : \quad |\psi\rangle \rightarrow |\psi_{\perp}\rangle, \quad \langle\psi|\psi_{\perp}\rangle = 0.$$

This transformation is forbidden by the laws of quantum physics.

V. Bužek, M. Hillery, and R.F. Werner, Phys. Rev. A **60**, 2626(R) (1999).

Linear optical quantum CZ gate



The three beam splitters BS, BS_A, and BS_B are identical.

Parameters of the beam splitters:

$$T = \frac{1}{3}, \quad R = \frac{2}{3}$$

$$T + R = 1$$

Qubits are encoded into states of single photons propagating in pairs of optical modes.

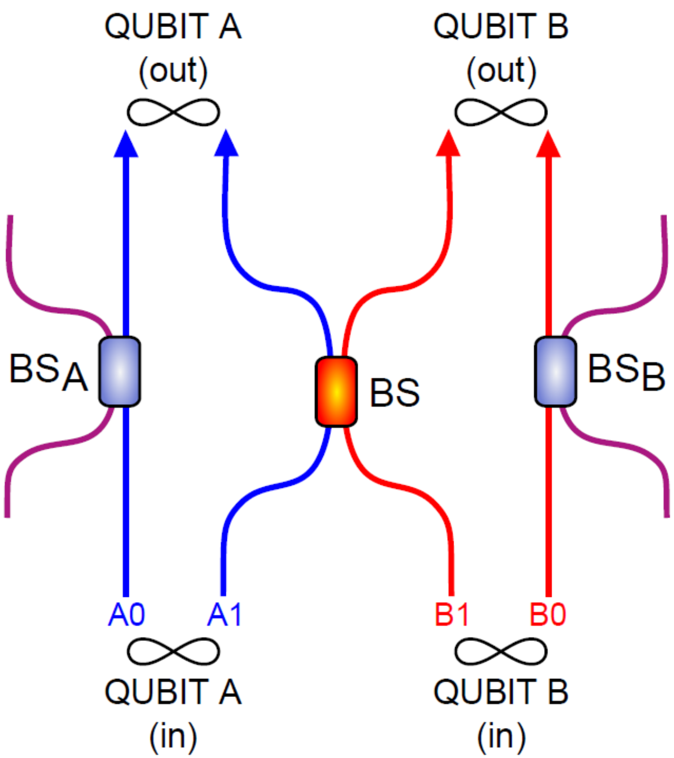
The gate operates in the coincidence basis.

N. K. Langford et al., Phys. Rev. Lett. **95**, 210504 (2005).

N. Kiesel et al., Phys. Rev. Lett. **95**, 210505 (2005).

R. Okamoto et al., Phys. Rev. Lett. **95**, 210506 (2005).

Linear optical quantum CZ gate



Conditional transformation of the four basis states:

$$
\begin{aligned}
|00\rangle &\rightarrow T|00\rangle, \\
|01\rangle &\rightarrow T|01\rangle, \\
|10\rangle &\rightarrow T|10\rangle, \\
|11\rangle &\rightarrow (1-2R)|11\rangle.
\end{aligned}
$$

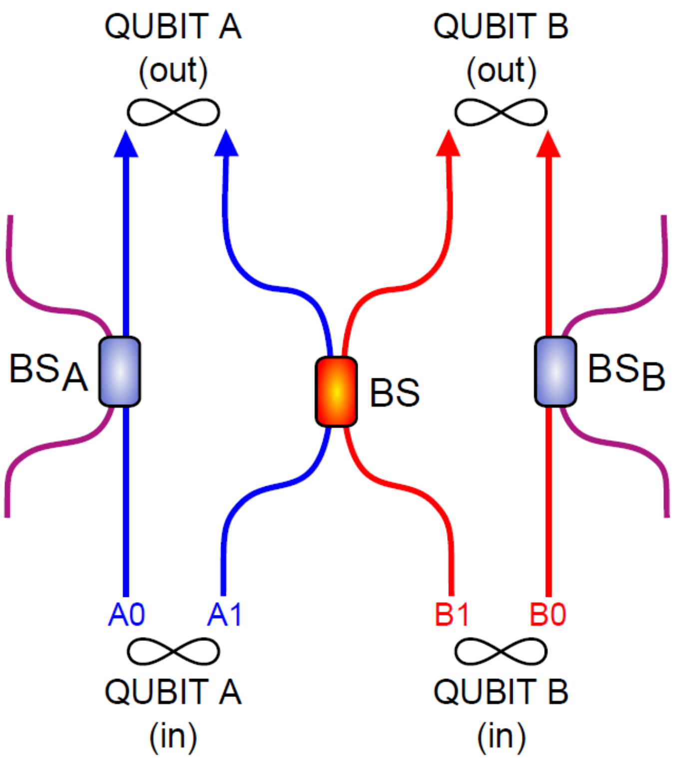
$$1-2R=-T \;\Rightarrow\; R=\frac{2}{3}$$

Qubits are encoded into states of single photons propagating in pairs of optical modes.

The gate operates in the coincidence basis.

N. K. Langford et al., Phys. Rev. Lett. **95**, 210504 (2005).
N. Kiesel et al., Phys. Rev. Lett. **95**, 210505 (2005).
R. Okamoto et al., Phys. Rev. Lett. **95**, 210506 (2005).

Weak interferometric coupling



Hamiltonian describing
the beam splitter type coupling:

$$H = i\hbar\kappa\left(ab^{+} - a^{+}b\right)$$

Parameters of the central beam splitter BS:

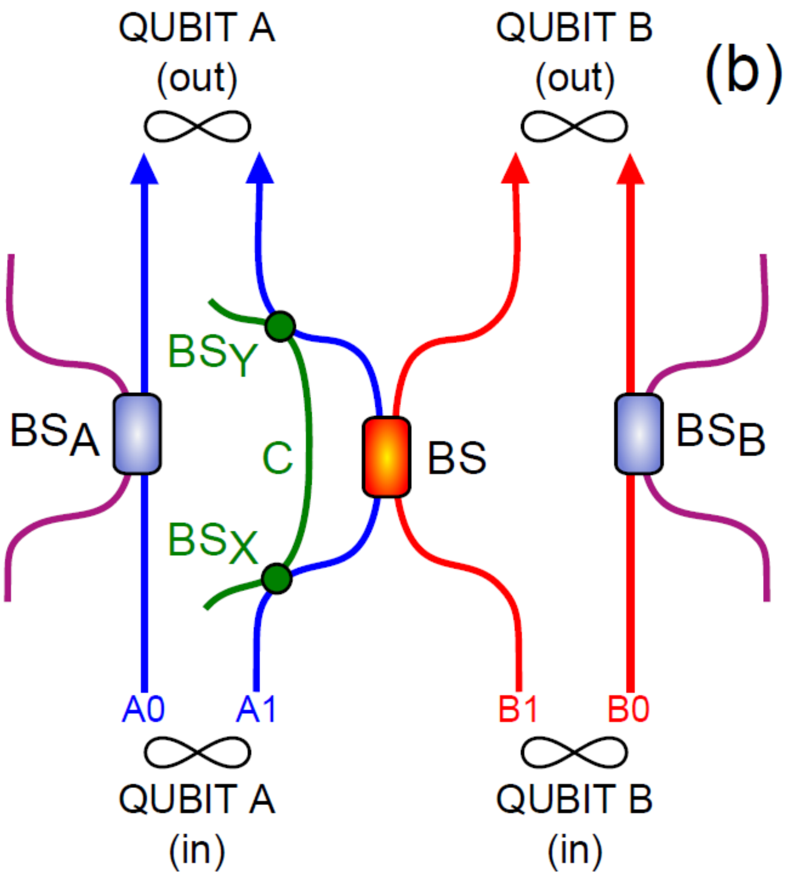
$$T = \cos^{2}(\kappa t)$$

$$R = \sin^{2}(\kappa t)$$

Consider implementations of hybrid quantum CZ gate between light and matter such as atomic ensembles or mechanical oscillators [4].

The achievable coupling strength κt may be limited by decoherence and other factors.

Quantum CZ gate with weak interferometric coupling

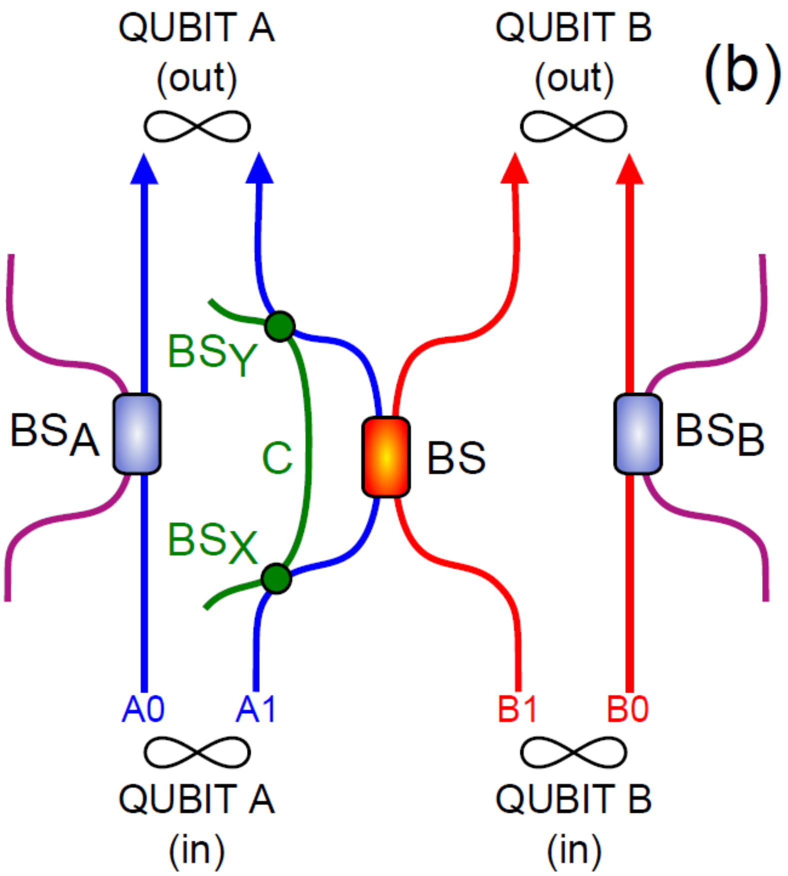


Mode A1 is coupled to auxiliary mode C

Suitable choice of the coupling to the auxiliary mode C and of the transmittance of BS_A and BS_B ensures successful implementation of the gate for arbitrarily small reflectance R of the central beam splitter BS.

The gate operates in the coincidence basis. The success is heralded by presence of a single photon in each pair of output modes (A0,A1), (B0,B1).

Parameters of the beam splitters



Formulas for amplitude transmittances and reflectances:

$$t_A = t t_X t_Y + r_X r_Y$$

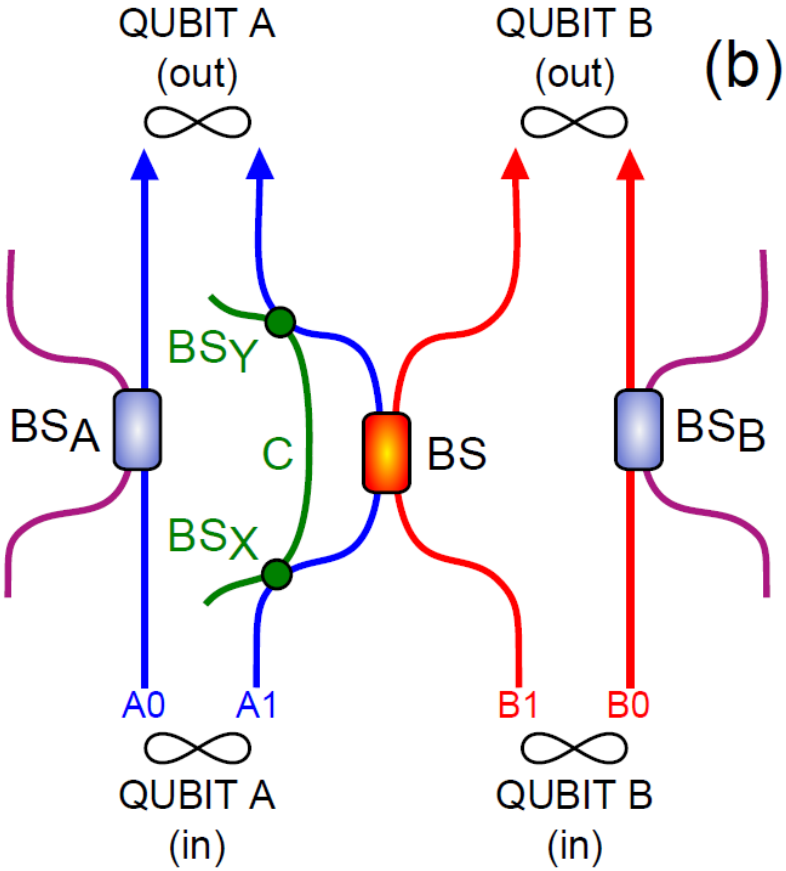
$$t_B = t$$

$$\frac{r_X r_Y}{t_X t_Y} = \frac{3R-2}{2t}$$

We obtain a whole one-parametric class of solutions.

We can optimize the free parameter t_X to maximize the success probability of the gate.

Success probability of the gate



Success probability of the gate:

$$P_S = \frac{1}{4} R^2 t_X^2 t_Y^2$$

Optimal amplitude transmittances and reflectances:

$$t_X^2 = t_Y^2 = \frac{2t}{2t + |3R - 2|}$$

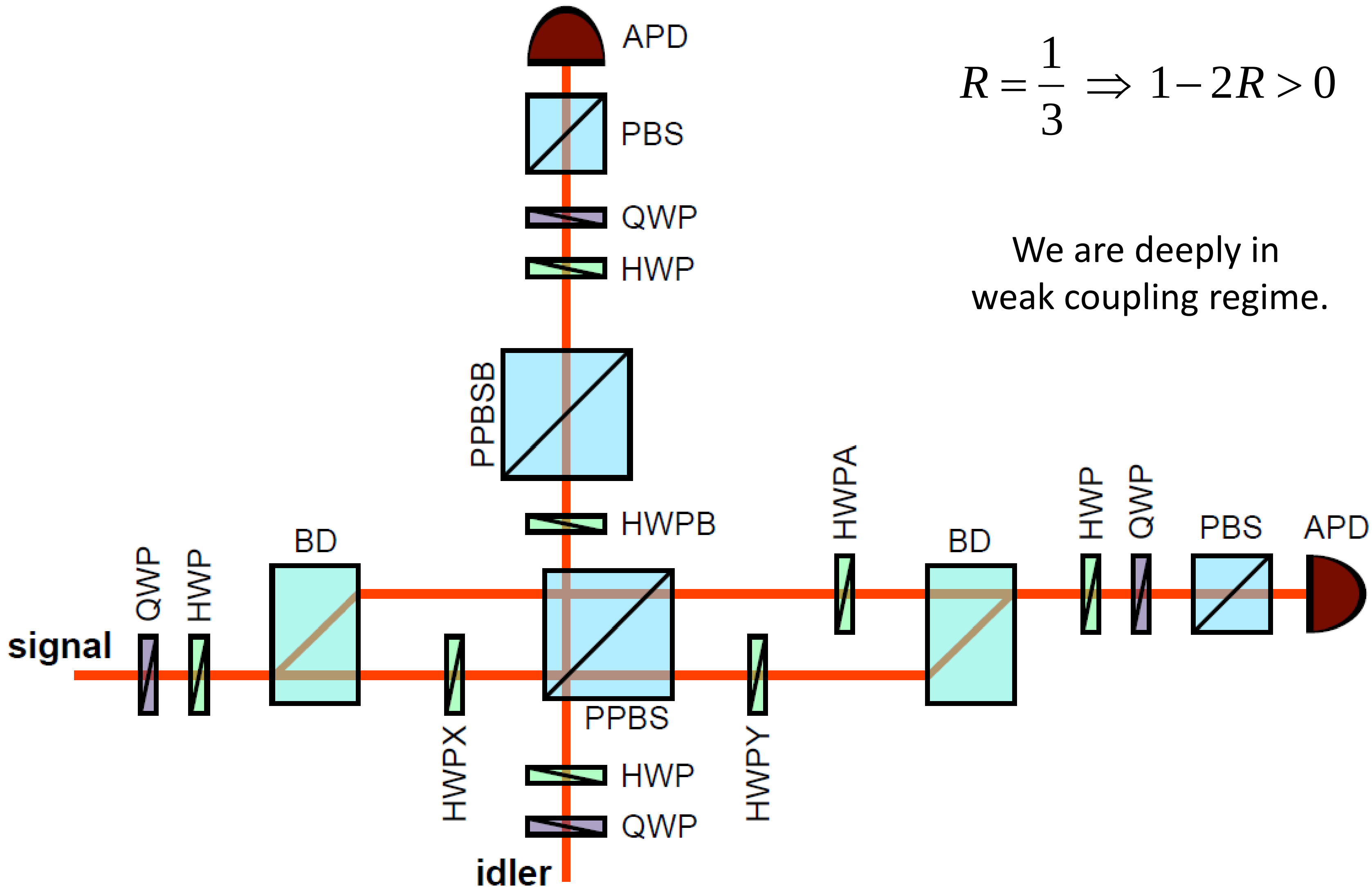
Maximal success probability:

$$P_S = \frac{TR^2}{(2t + |3R - 2|)^2}$$

P_S should be compared with the probability 1/9 of the ordinary linear optical CZ gate with R=2/3.

We achieve enhanced interaction strength at the cost of reduced success probability.

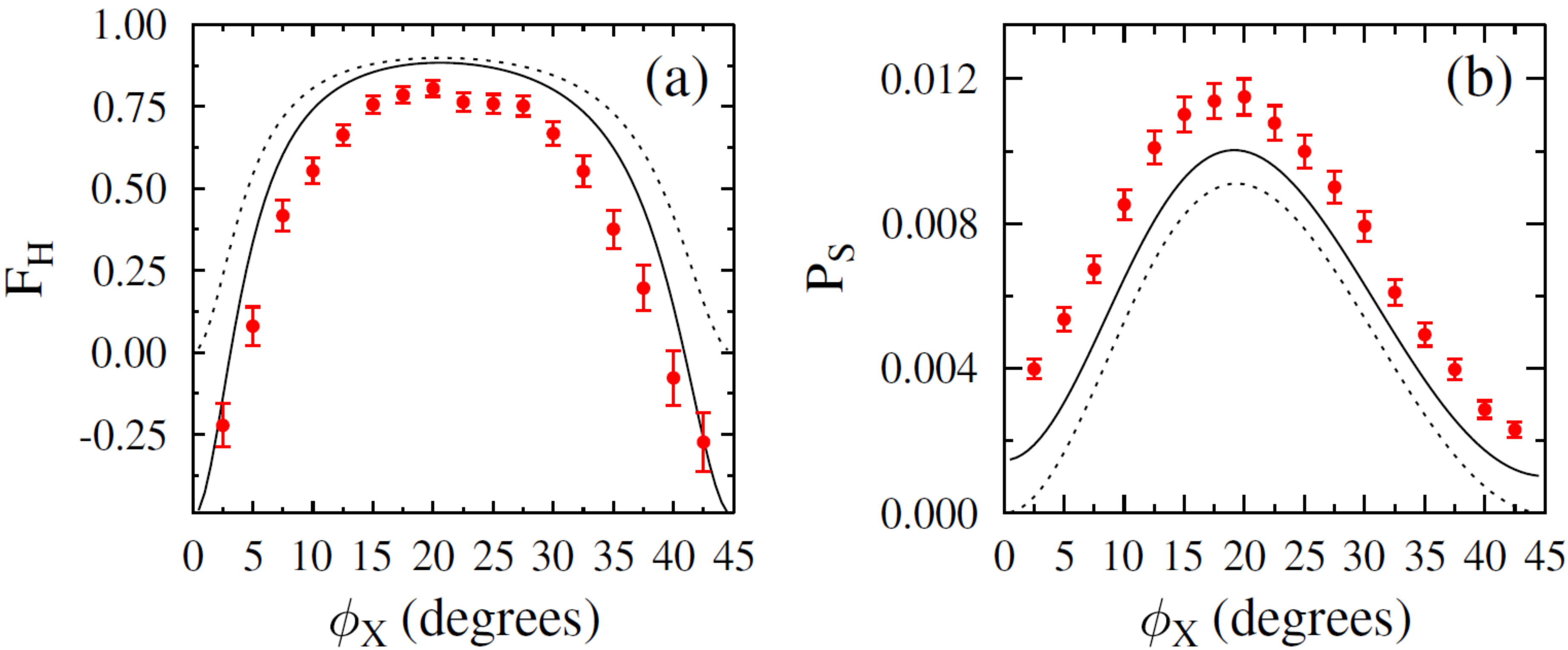
Experimental setup



$$R = \frac{1}{3} \Rightarrow 1 - 2R > 0$$

We are deeply in
weak coupling regime.

Experimental characterization of the CZ gate



Hofmann lower bound on quantum gate fidelity

Success probability of the gate

Solid lines represent predictions of a theoretical model accounting for experimental imperfections.

Experimental quantum process tomography

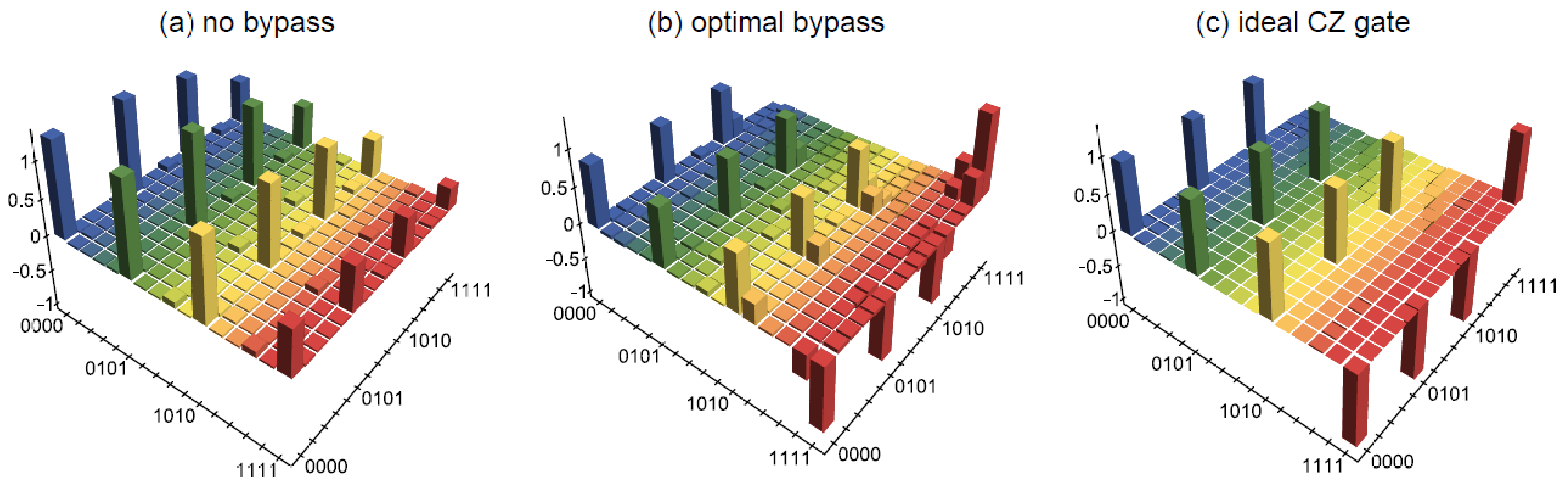
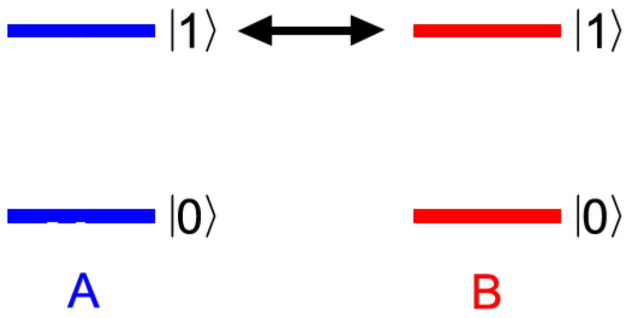


FIG. 5. (Color online) Quantum process tomography of the CZ gate. Reconstructed quantum process matrices χ of two-qubit operation without bypass (a) and with optimal bypass (b). For comparison, the ideal CZ gate is shown in panel (c). For ease of comparison, all process matrices are normalized so that $\mathrm{Tr}[\chi] = 4$. Experimentally determined success probability of the CZ gate shown in panel (b) reads $P_S = 1.15(2)\%$.

Full quantum process tomography of the CZ gate performed at the optimal operating point where both gate fidelity and success probability are maximized.

Gate fidelity calculated from the reconstructed quantum process matrix: **F=0.846**

Quantum CZ gate for weak spin-spin coupling



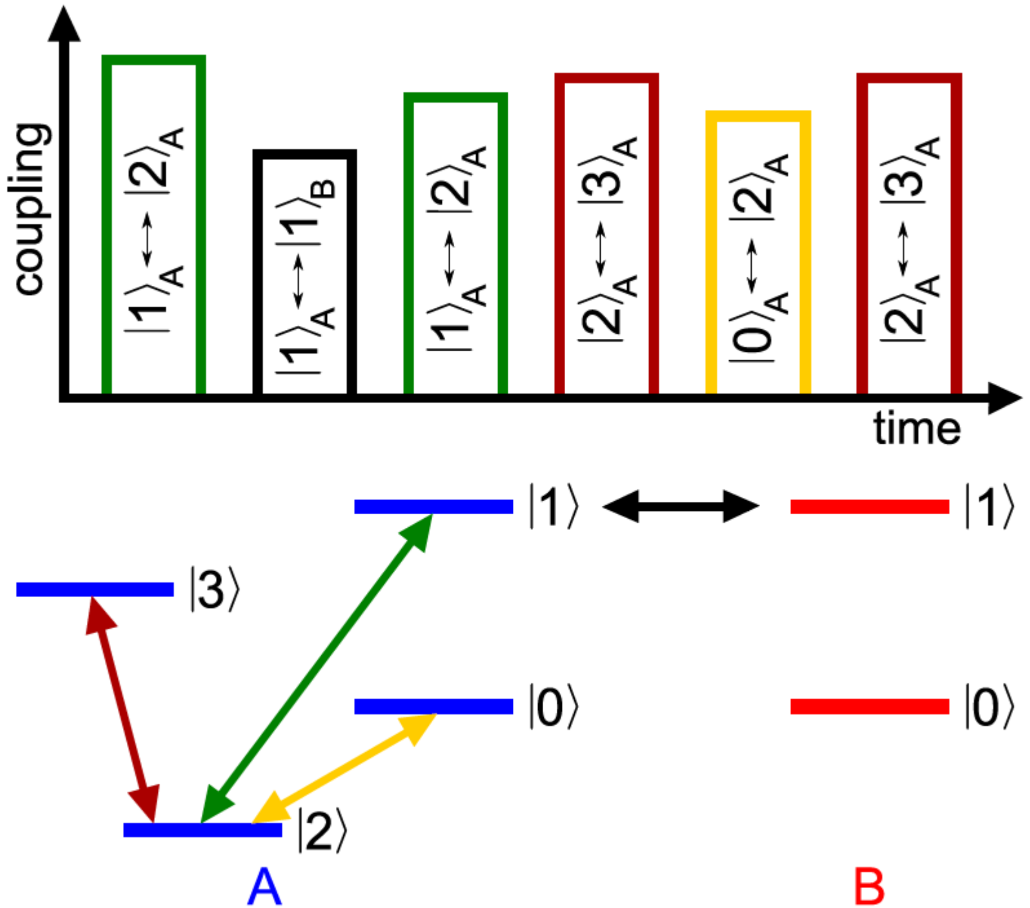
Interaction of qubits A and B results in a controlled-phase gate:

$$U_\phi = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\phi} \end{pmatrix}$$

Two weakly interacting atoms, ions or spins.

The conditional phase shift ϕ provides a natural measure of the interaction strength.

Quantum CZ gate for weak spin-spin coupling



Two weakly interacting atoms, ions or spins.

Suitable choice of coupling to an auxiliary internal quantum level |2> enables implementation of the CZ gate for arbitrary weak coupling ϕ.

Projection of particle A onto qubit subspace: driving auxiliary transition 2-3 and conditioning on the absence of fluorescence photons.

Conclusions

We have experimentally demonstrated orthogonalization of partly unknown single-qubit and two- qubit states by quantum filtering.

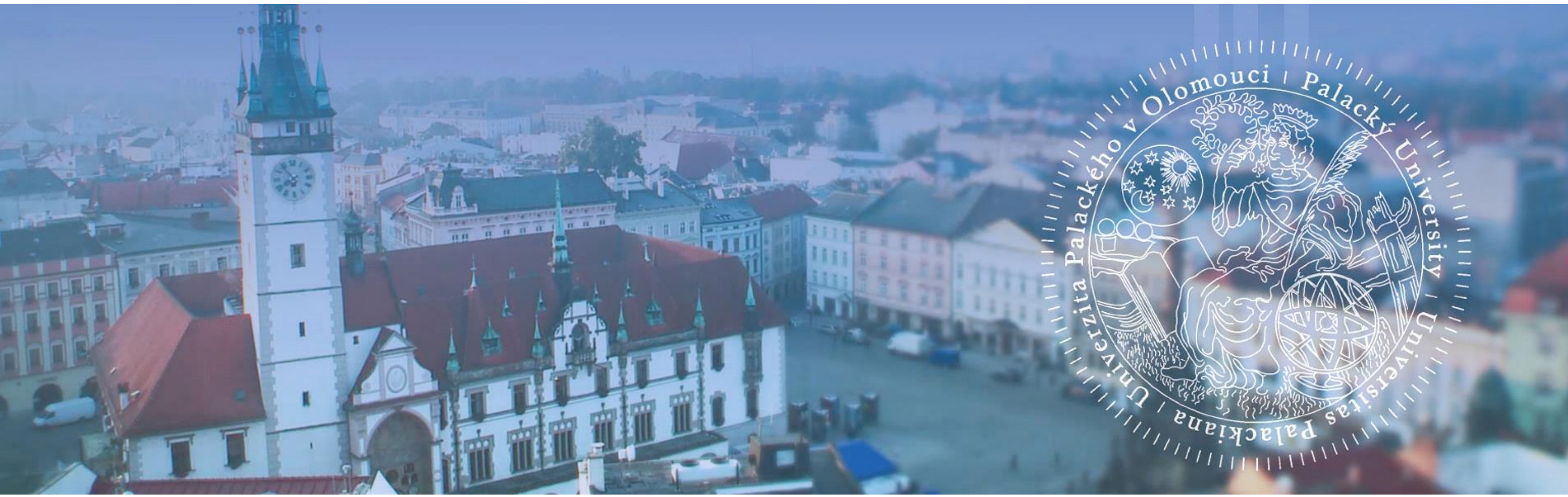
The required prior information is a knowledge of a mean value of an arbitrary single operator A.

The probabilistic orthogonalization significantly outperforms the best deterministic orthogonalization procedure.

Entangled states can be orthogonalizad by local filtering on one part of the state.

This procedure can be extended to preparation of superpositions of the input state and its orthogonal counterpart, see A.S. Coelho, L.S. Costanzo, A. Zavatta, C. Hughes, M. S. Kim, and M. Bellini, arXiv:1407.6644.

Thank you for your attention!



optics.upol.cz

www.opticsolomouc.org