Quantum Information Processing (Communication) with Photons

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

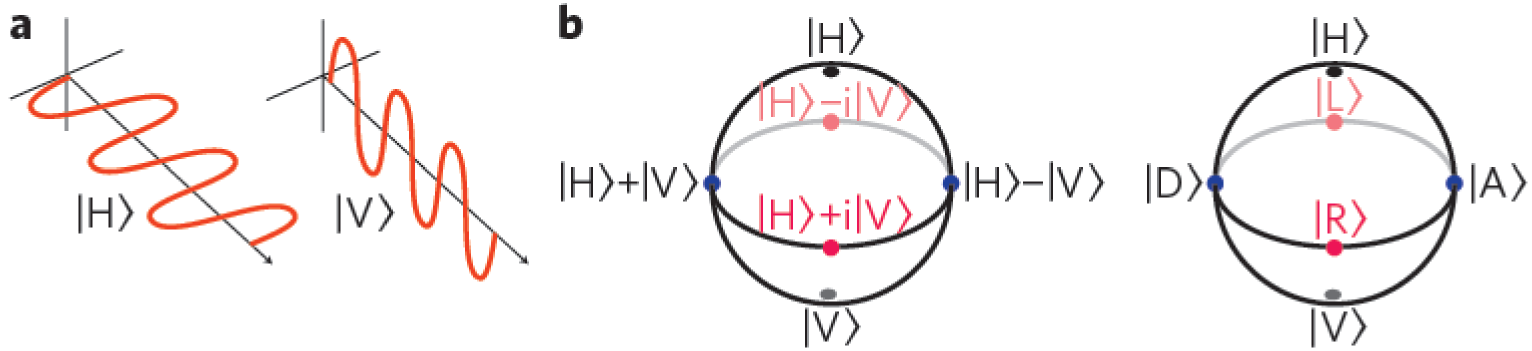
Why Photons?

- only **weak interaction** with environment (good coherence)
- high-speed (c), low-loss transmission ('flying qubits' for **long-distance quantum communication**)
- good **single qubit control** with standard optical components (waveplates, beamsplitters, mirrors,...)
- efficient **photon detectors** (photodiodes,...)
- **disadvantage: weak two-photon interactions**

  (requires non-linear medium -> two-qubit gates are hard)
- use initially entangled quantum state for:
  - (commercial) quantum cryptography
  - *super dense coding*, teleportation
  - fundamental tests of quantum mechanics (*Bell inequalities*)
  - one-way quantum computing

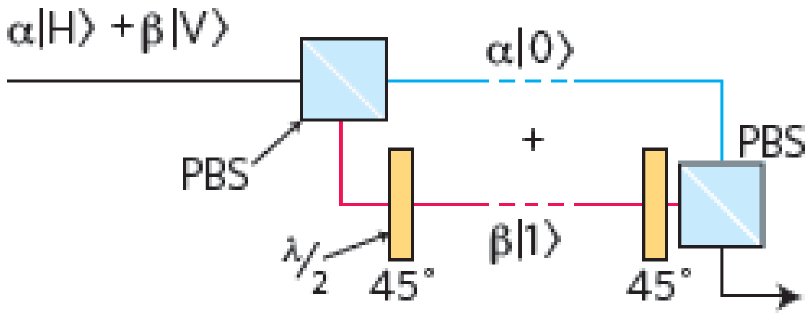
Encoding of quantum information

- polarisation



O'Brien et al., Nature Photonics (2009)

- spatial mode



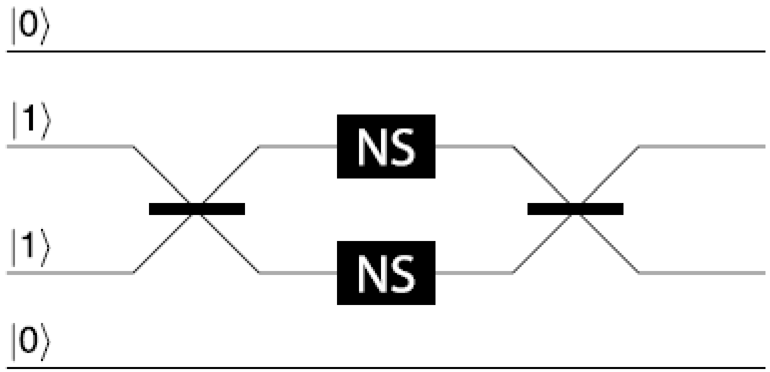
- angular momentum, etc...

Linear Optics Quantum Computation – KLM scheme

Idea: Use only beam-splitters, phase shifters, single photon sources and photo-detectors to implement single and two-qubit gates [Knill-Laflamme-Milburn, Nature 409 (2001)]

Prize to pay: non-deterministic + ancilla photons

optical CNOT-gate based on non-linear sign shift gate (NS)

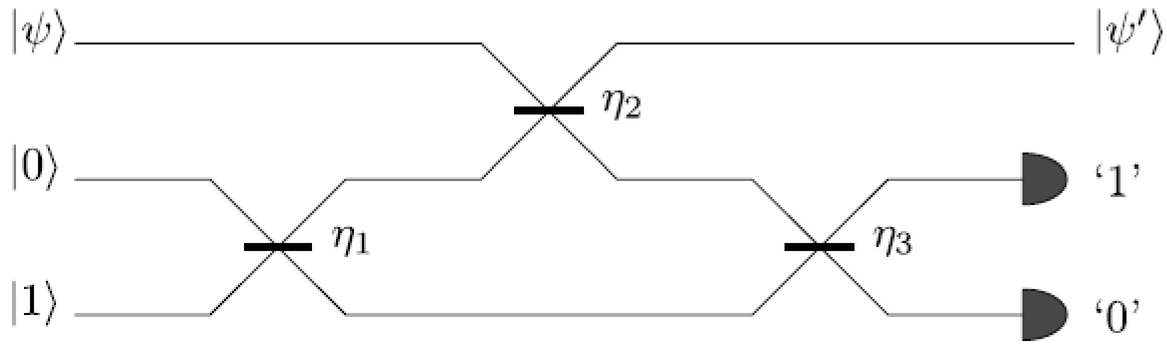


[Kok, 2010]

Linear Optics Quantum Computation – KLM scheme

Non-linear sign gate (NS): $\alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle - \gamma|2\rangle$

only if a photon is detected in the upper detector and none in the lower, the gate was successful



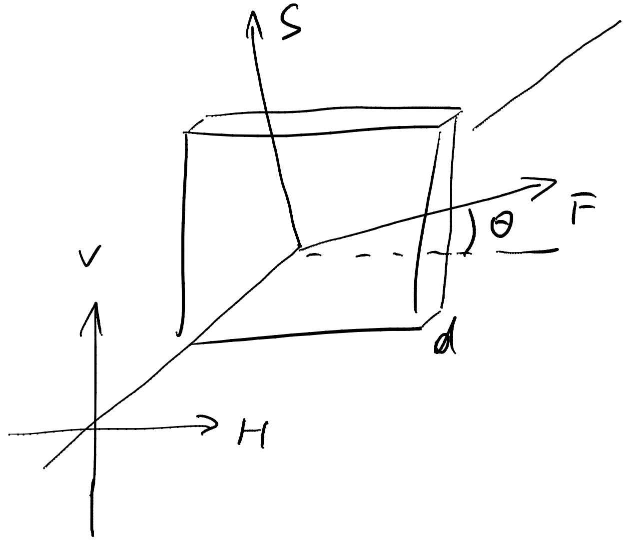
[Kok, 2010; KLM, Nature, 2001]

transmission probabilities: η1 = η3 ~ 85%; η2 ~ 17%

success probability: 25%
# of ancilla photons: 2

Wave plates

- birefringent material: polarisation-dependent wave velocity



- F: fast axis, parallel to optical axis
  S: slow axis, perpendicular to opt. axis
- phase shift

$$\phi_i = k_i d = \frac{v_i}{c} k d = \frac{k}{n_i} d$$

n_i…refractive index (i=F,S)

$$n_S > n_F$$

- **half-wave plate:** π– phase shift between fast and slow component

$$\phi_F - \phi_S = \pi$$

$$\frac{k}{n_F} d - \frac{k}{n_S} d = \pi$$

$$d = \frac{\lambda}{2}(n_F - n_S)$$

Half-wave plate

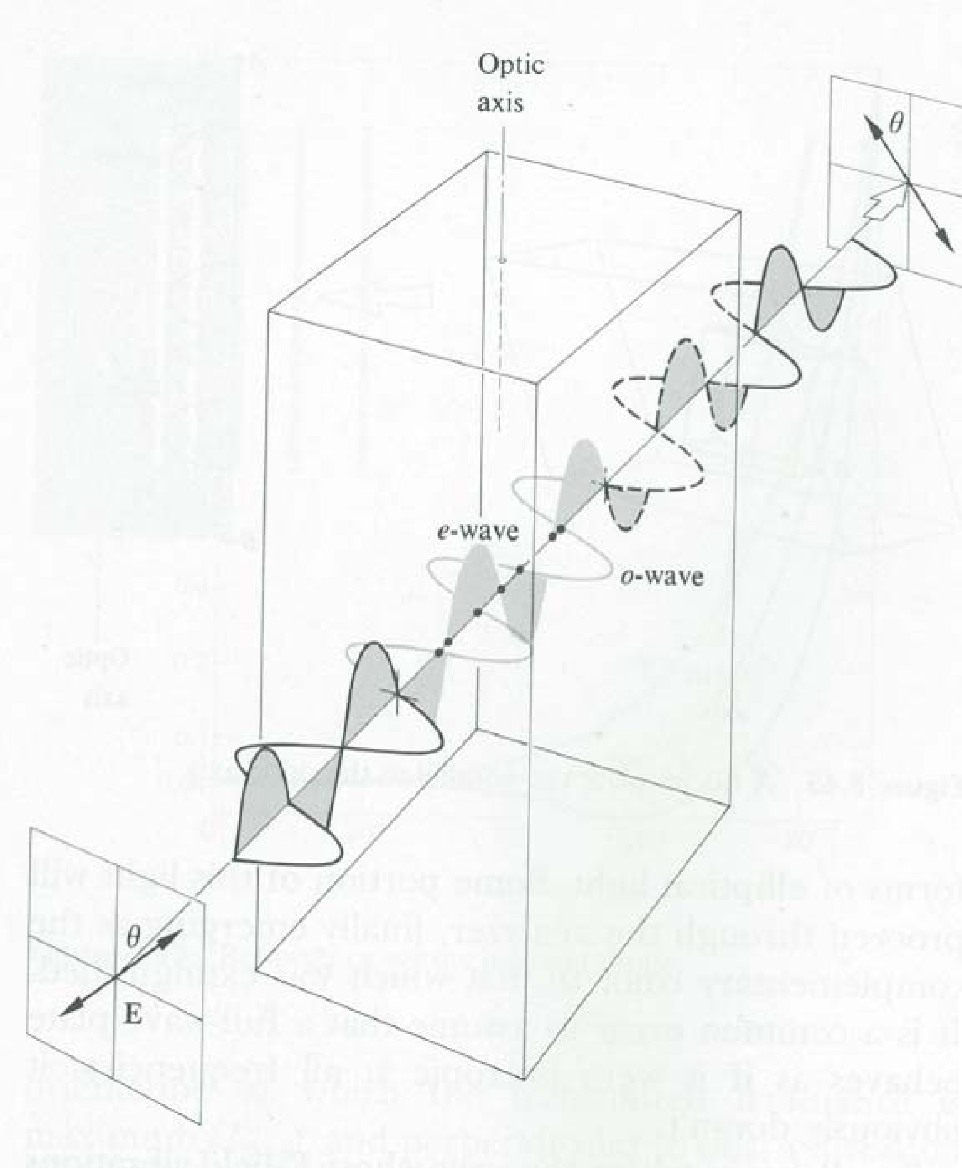
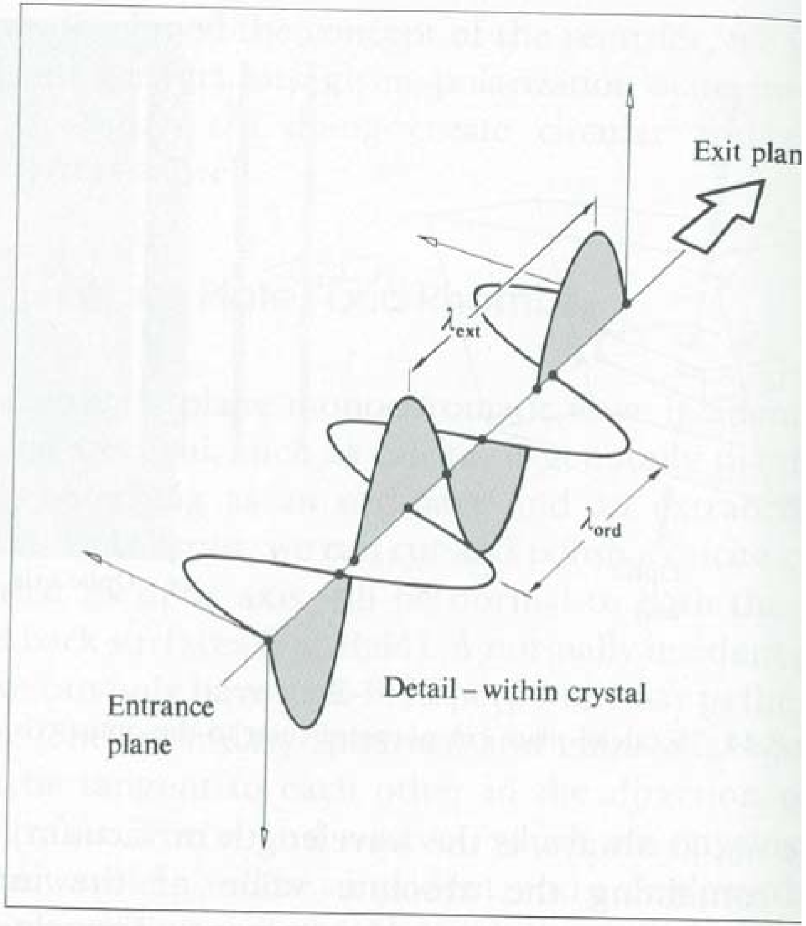


Figure 8.46 A half-wave plate.



Waveplates - Operations

half-wave plate:

$$|H\rangle \rightarrow \cos 2\theta |H\rangle + i \sin 2\theta |V\rangle$$
$$|V\rangle \rightarrow i \sin 2\theta |H\rangle + \cos \theta |V\rangle$$

$$U_{HWP}(\theta) = \begin{pmatrix} \cos 2\theta & i \sin 2\theta \\ i \sin 2\theta & \cos 2\theta \end{pmatrix}$$ →π–rotation about **x-axis**

for θ=π/4: $$U_X = e^{i\pi/2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \equiv X$$ $U_X|V\rangle = |H\rangle$; $U_X|H\rangle = |V\rangle$

quarter-wave plate: $$\phi_F - \phi_S = \pi/2, \qquad \theta = \pi/4$$

(linear -> circular)

$$U_Z = e^{-i\pi/4} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \equiv Z$$ → π/2-rotation about z-**axis**

$$|L\rangle = \frac{1}{\sqrt{2}} (|H\rangle + i|V\rangle) \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix}$$

$U_Z|L\rangle \propto (|H\rangle - |V\rangle)/\sqrt{2} = |A\rangle$

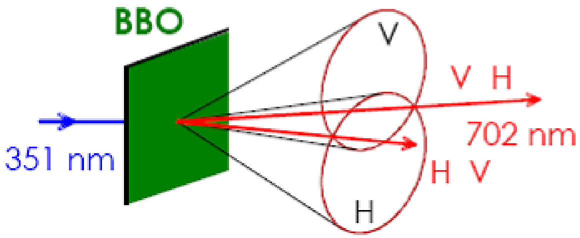
λ/2 and λ/4 wave plates are sufficient for QIP!

Entanglement creation - Parametric Down Conversion

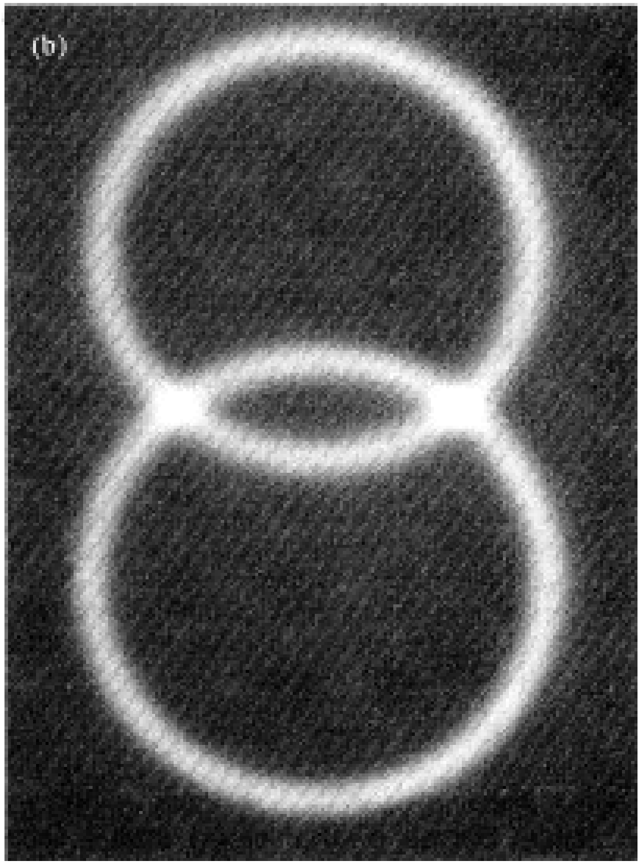
Generation of entangled photon pairs using nonlinear medium
(BBO (beta barium borate) crystal)

parametric down-conversion

- 1 UV-photon ➔ 2 "red" photons
- conservation of
  - energy $\omega_p = \omega_s + \omega_i$
  - momentum $\vec{k}_p = \vec{k}_s + \vec{k}_i$
- Polarisationskorrelationen (typ II)



$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle - |V\rangle|H\rangle\right)$$



Kwiat et al., PRL 75 (1997).

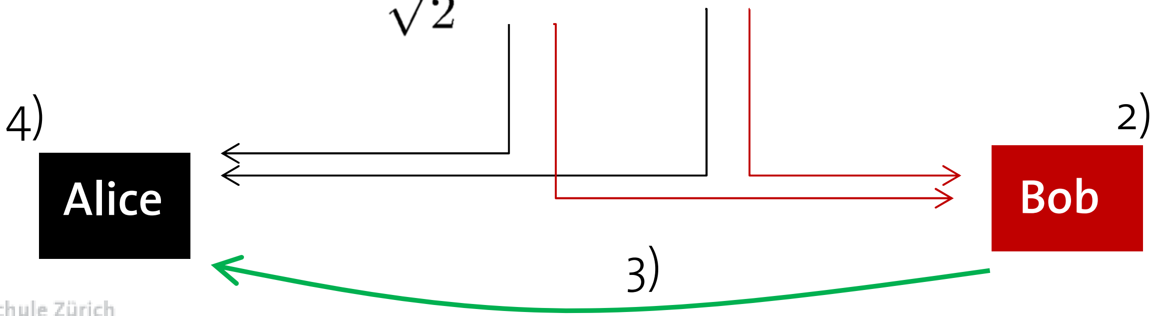
Superdense Coding

task: Transmit two bits of classical information between Alice (A) and Bob (B) using only one qubit. Alice and Bob share an entangled qubit pair prepared ahead of time.

protocol:

1) Alice and Bob each have one qubit of an entangled pair
2) Bob does a quantum operation on his qubit depending on which 2 classical bits he wants to communicate
3) Bob sends his qubit to Alice
4) Alice does one measurement on the entangled pair

1) $$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|HV\rangle + |VH\rangle\right)$$



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Superdense coding

bit to be transferred	Bob's operation	resulting 2-qubit state (Bell states)	Alice's measurement
00	I_2	$I_2 \lvert\psi\rangle = (\lvert HV\rangle + \lvert VH\rangle)/\sqrt{2} = \lvert\Psi^+\rangle$	$\lvert\Psi^+\rangle$
01	X_2 (HWP)	$X_2 \lvert\psi\rangle = (\lvert HH\rangle + \lvert VV\rangle)/\sqrt{2} = \lvert\Phi^+\rangle$	$\lvert\Phi^+\rangle$
10	Z_2(QWP)	$Z_2 \lvert\psi\rangle = (\lvert HV\rangle - \lvert VH\rangle)/\sqrt{2} = \lvert\Psi^-\rangle$	$\lvert\Psi^-\rangle$
11	X_2Z_2 (HWP + QWP)	$X_2Z_2 \lvert\psi\rangle = (\lvert HH\rangle - \lvert VV\rangle)/\sqrt{2} = \lvert\Phi^-\rangle$	$\lvert\Phi^-\rangle$

- two qubits are involved in protocol BUT Bob only interacts with one and sends only one along his quantum communications channel
- two bits cannot be communicated sending a single classical bit along a classical communications channel

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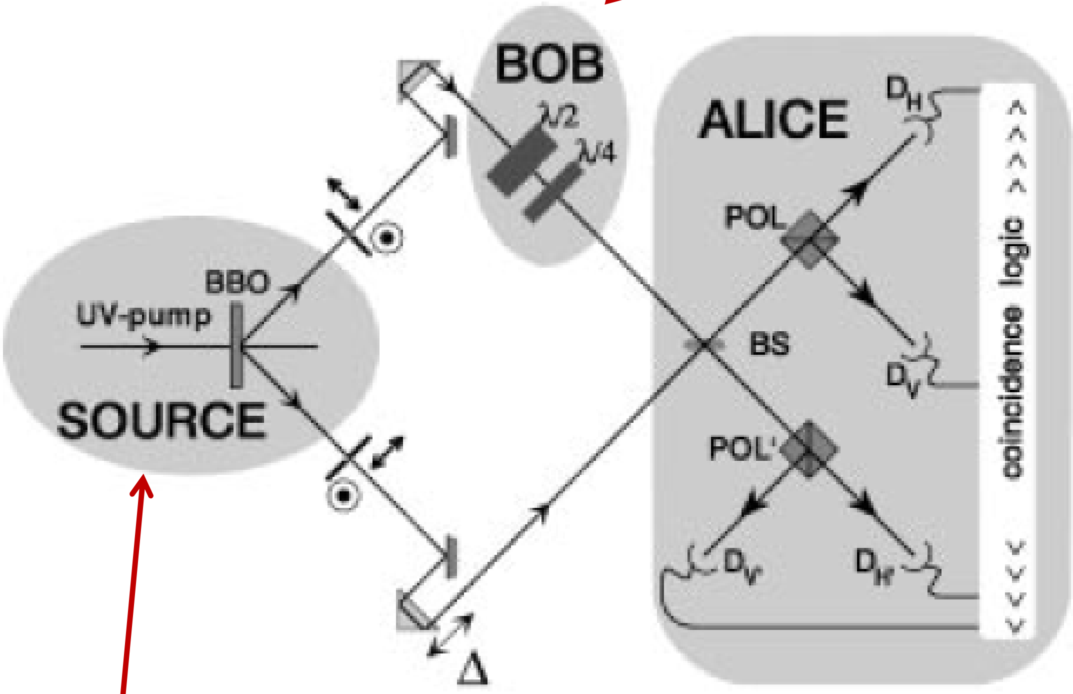
Bennett & Wiesner, Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states, Phys Rev Lett 60, 2881 (1992).

Realization of superdense coding

state manipulation



preparation of entangled pair

Bell state measurement

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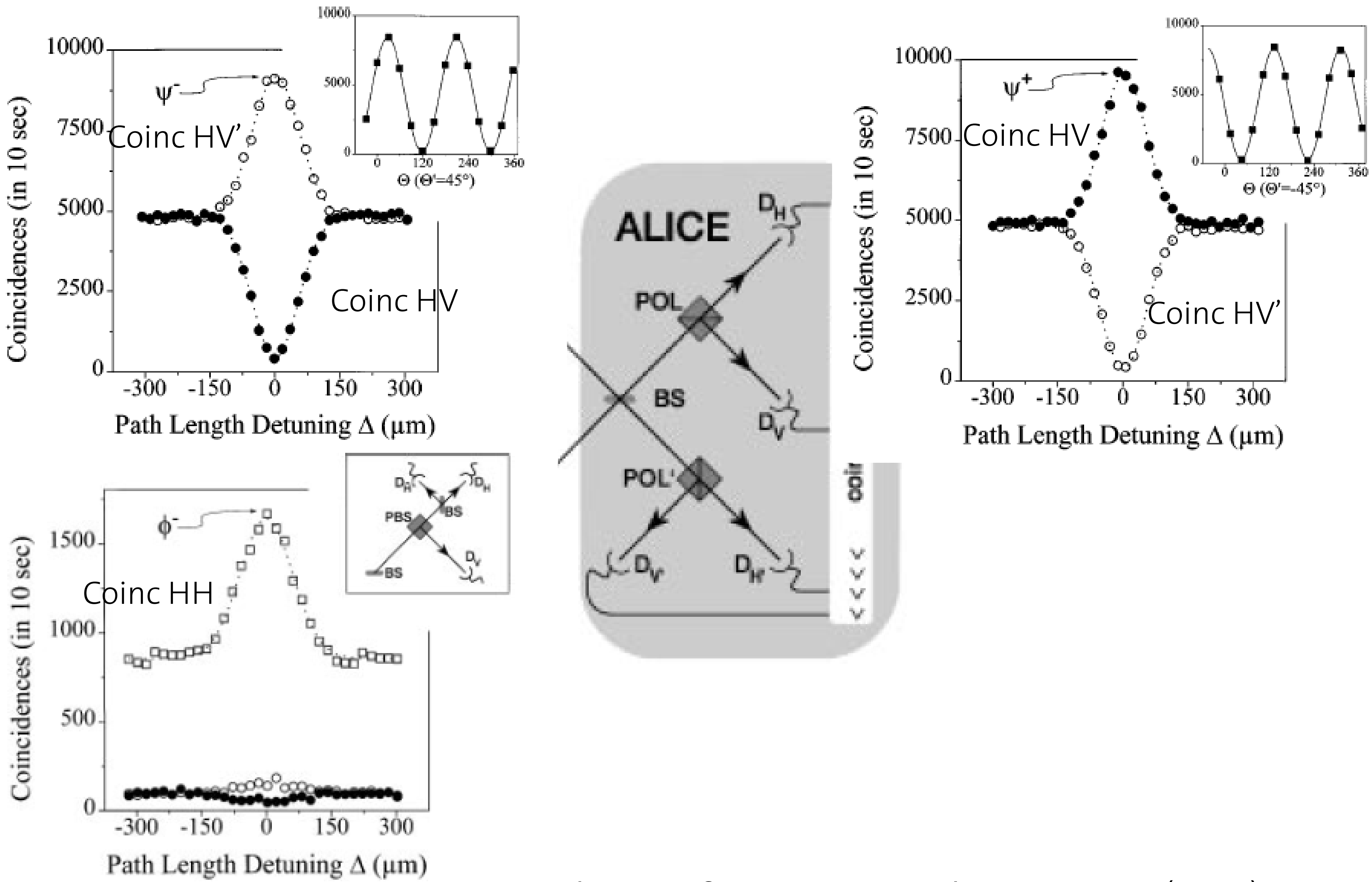
Mantle, Weinfurter, Kwiat, Zeilinger, PRL 76 (1996)

Realization of superdense coding



Mantle, Weinfurter, Kwiat, Zeilinger, PRL 76 (1996)