# Quantum Information Processing (Communication) with Photons

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

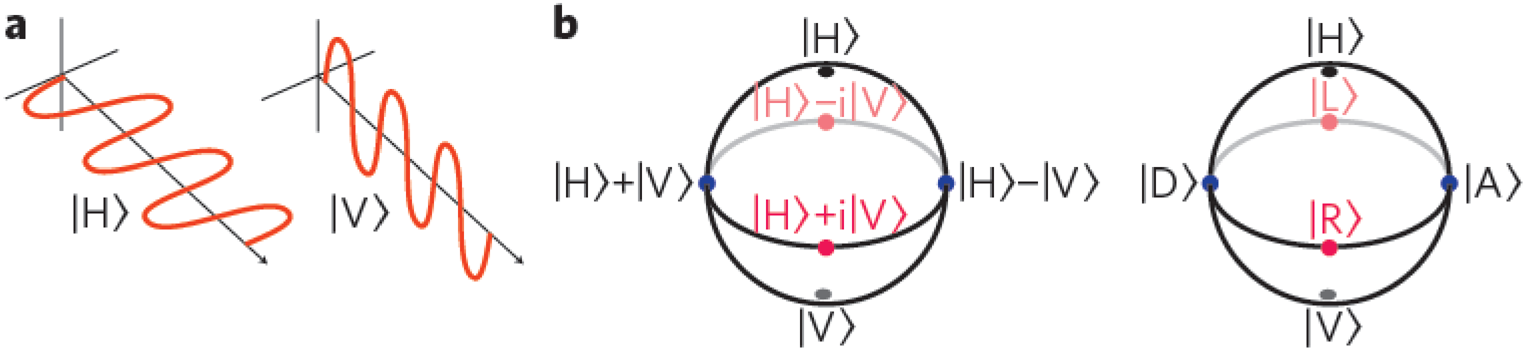
# Why Photons?

- 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

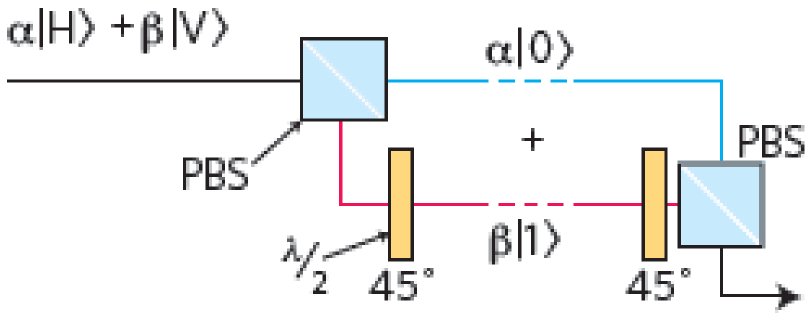
# Encoding of quantum information

- polarisation




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

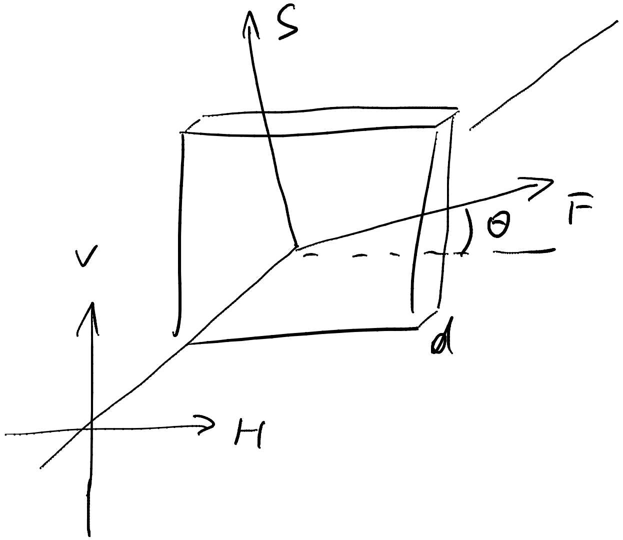
- spatial mode




- angular momentum, etc...

# 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:** $\pi$– 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

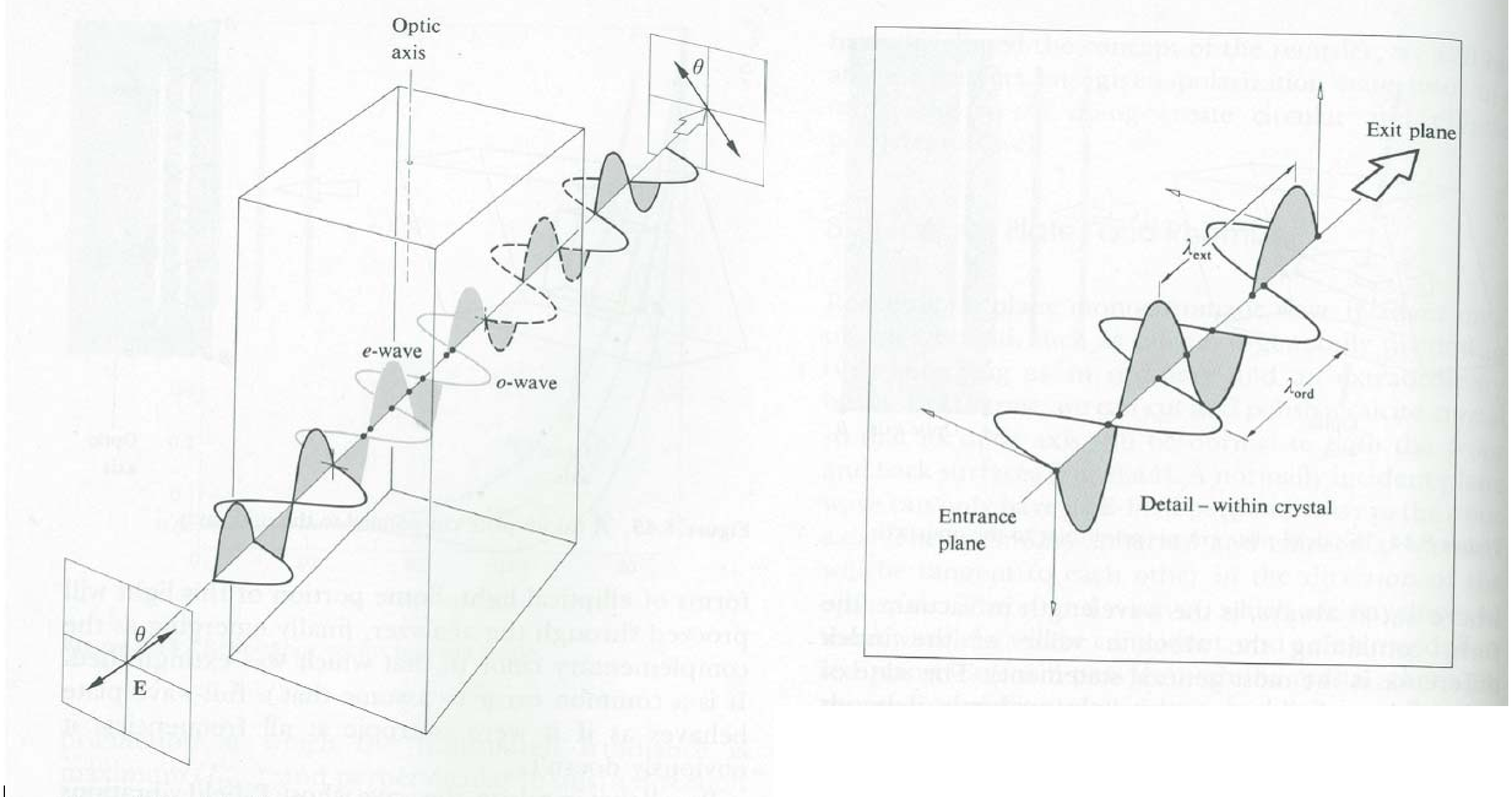


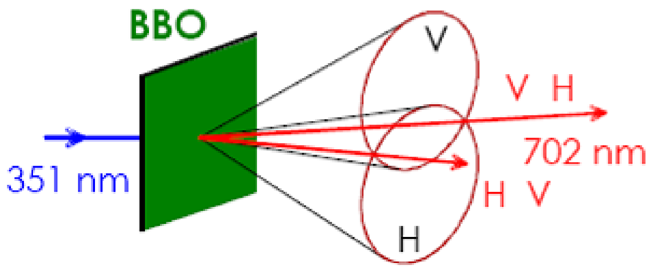

**Figure 8.46** A half-wave plate.

# Entanglement creation - Parametric Down Conversion

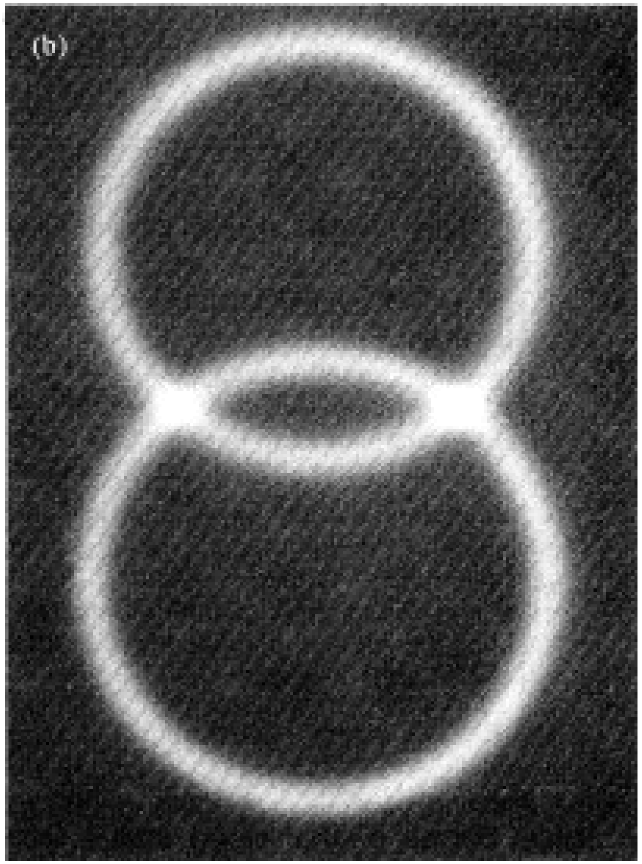
Generation of entangled photon pairs using nonlinear medium (BBO (beta barium borate) crystal)

## 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).

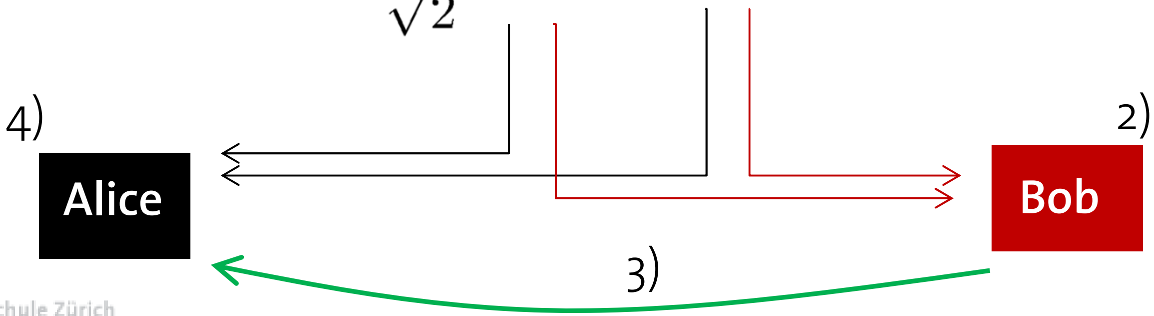
# Superdense Coding

**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

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



# Superdense coding

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

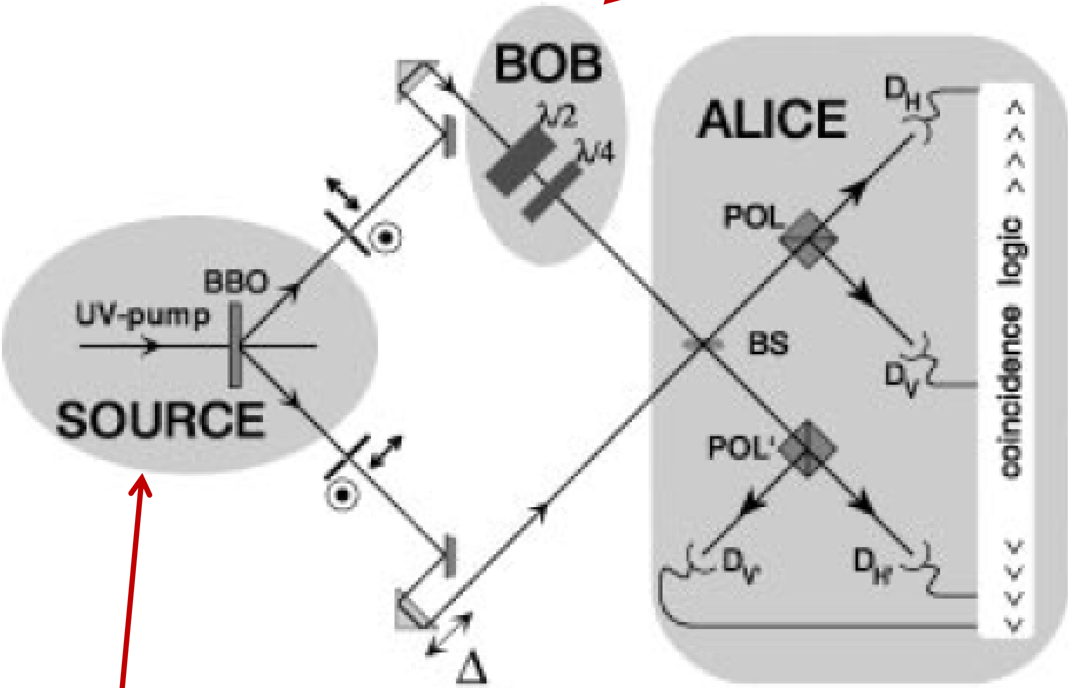
- two qubits are involved in protocol BUT Bob only interacts with one and sends only one along his quantum communications channel
- two bits cannot be communicated sending a single classical bit along a classical communications channel



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

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

# Realization of superdense coding

coincidence rates: