Quantum Information Processing (Communication) with Photons

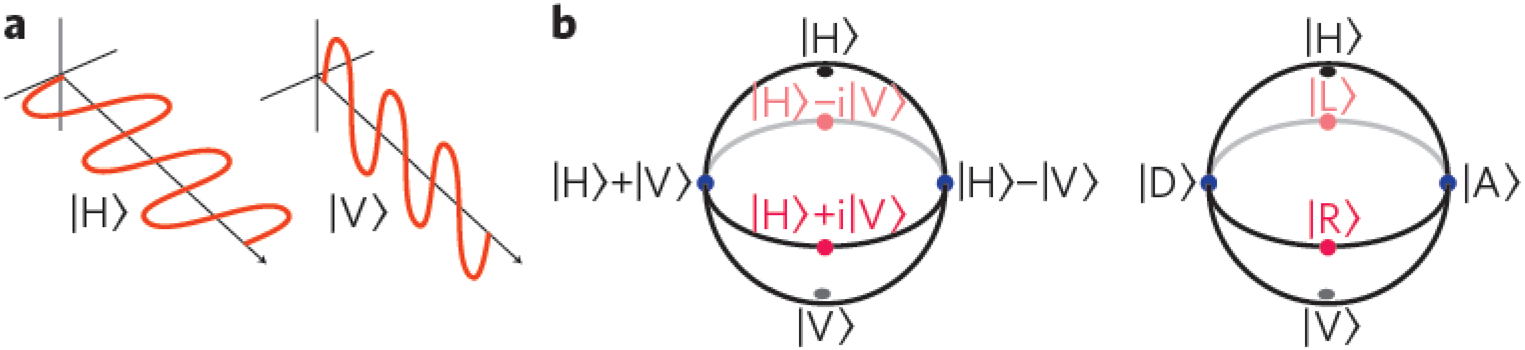
Why Photons?

- 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

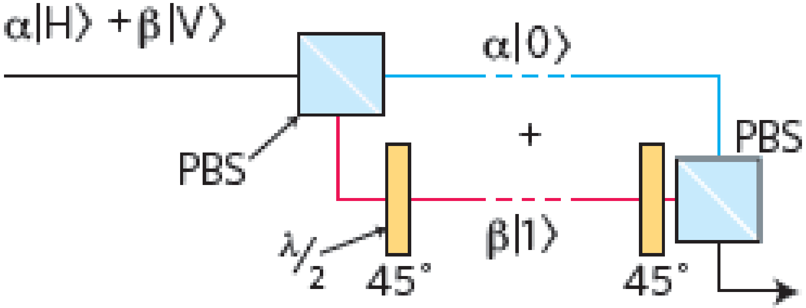
Encoding of quantum information

- polarisation



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

- spatial mode



- coherent state
- time-bin
- …

Half-wave plate

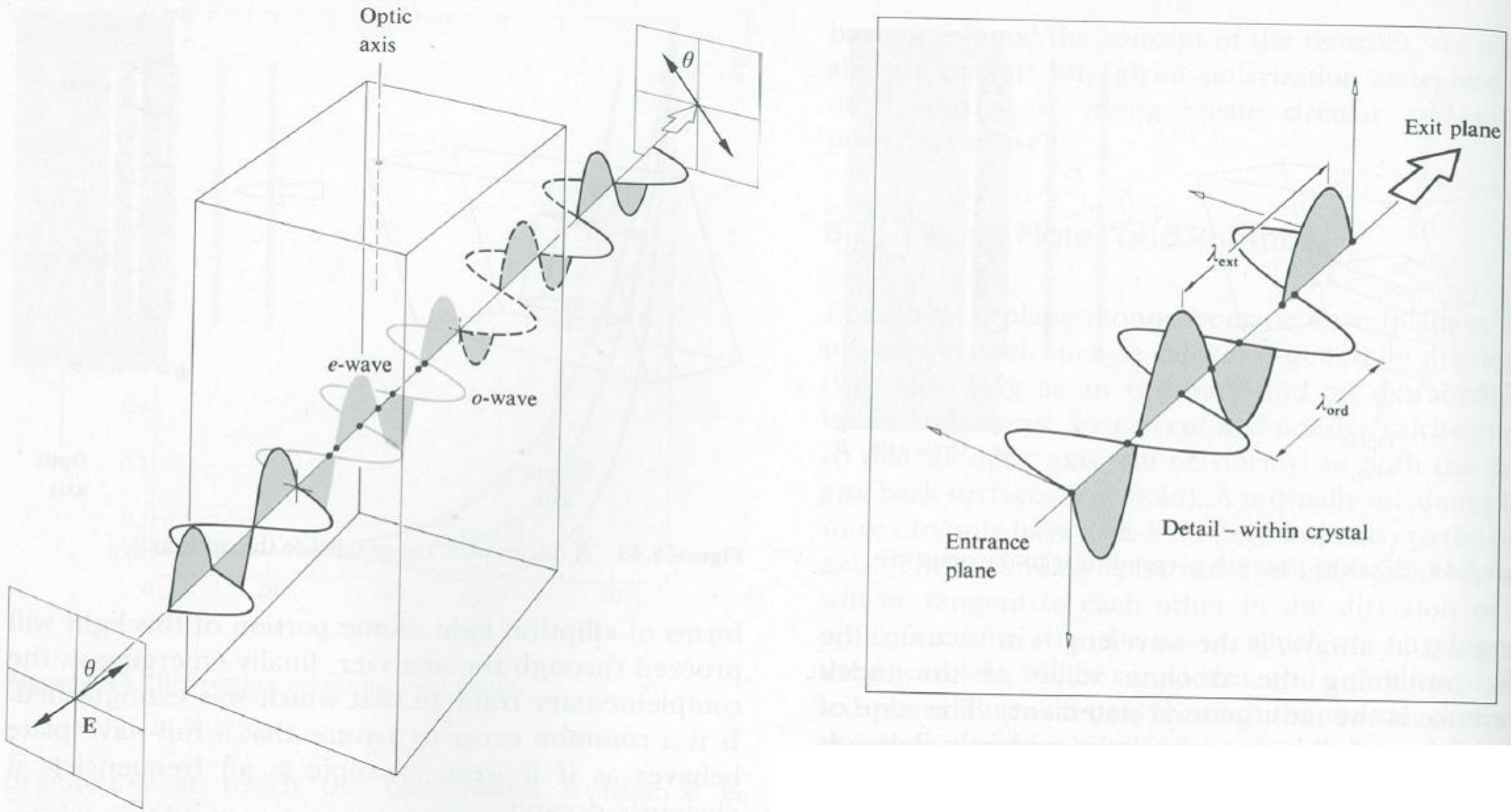


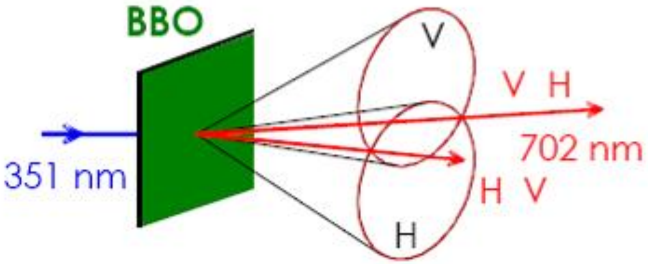
Figure 8.46 A half-wave plate.

Entanglement creation - Parametric Down Conversion

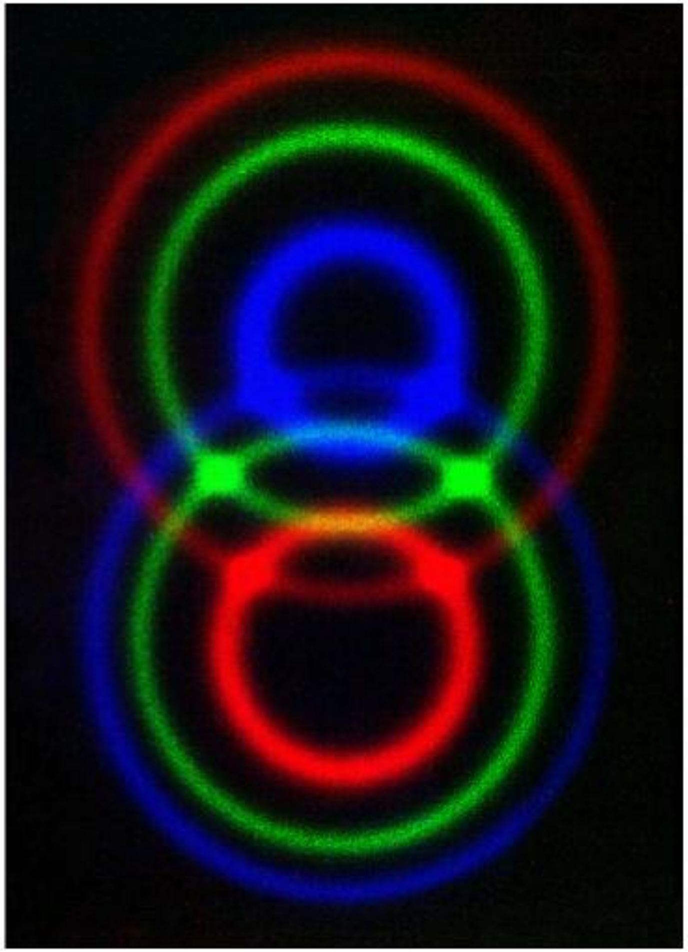
Generation of entangled photon pairs using nonlinear medium (BBO (beta barium borate) crystal)

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)



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

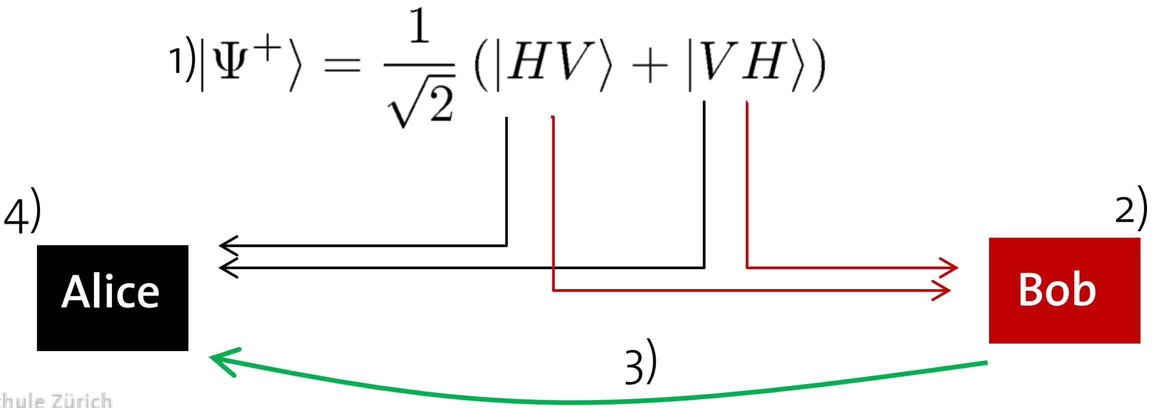


Superdense Coding

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 she wants to communicate
3) Bob sends his qubit to Alice
4) Alice does one measurement on the entangled pair



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

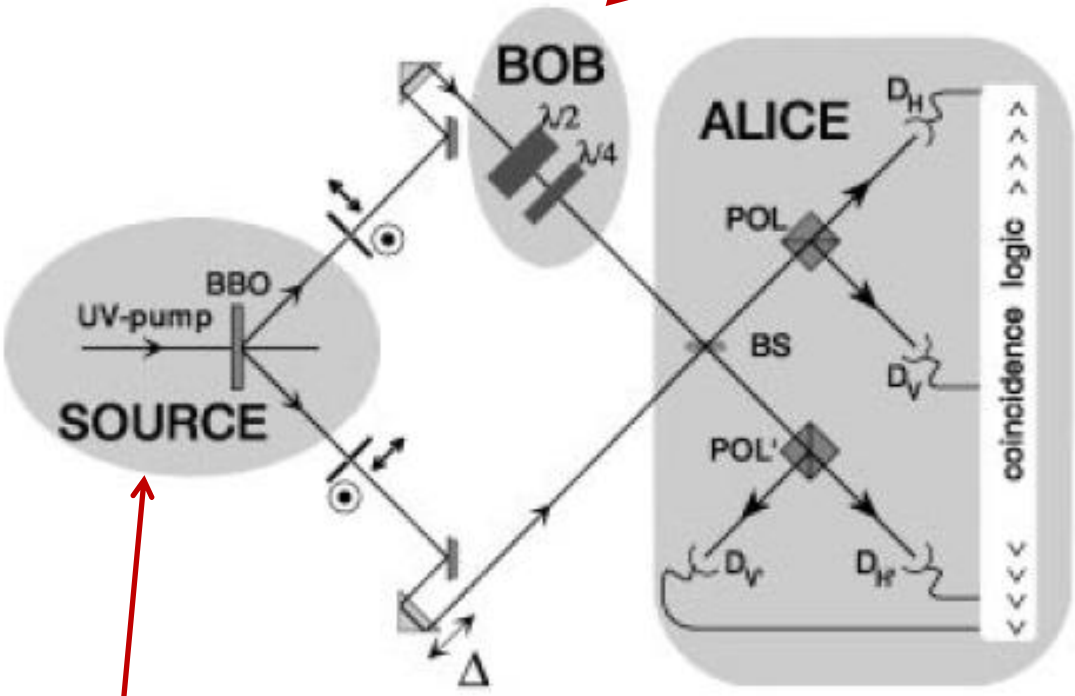
Superdense coding

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

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

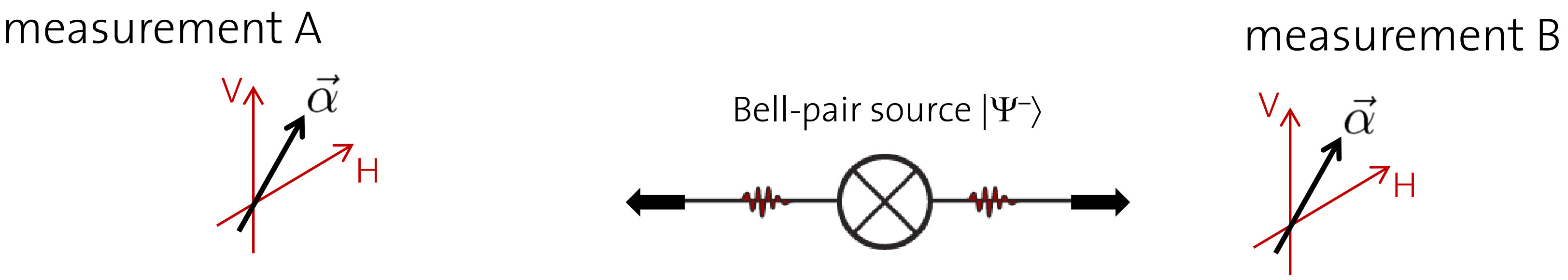
preparation of entangled pair

Bell state measurement

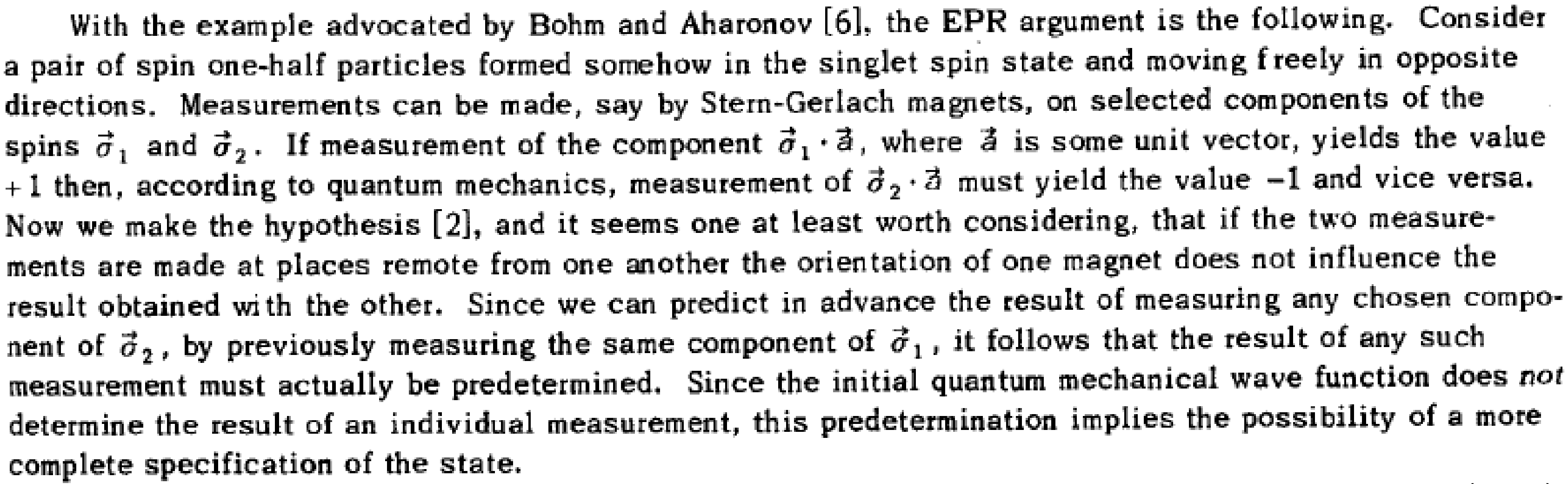
Bell Inequalities

EPR Paradox

singlet state: $|\Psi^-\rangle = (|HV\rangle - |VH\rangle)/\sqrt{2}$



- perfect anti-correlations (⟨A·B⟩=-1), independent of $\vec{\alpha}$
- measurement A determines state at B, even if spatially separated
- possible conclusion: wave function description incomplete!



With the example advocated by Bohm and Aharonov [6], the EPR argument is the following. Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins $\vec{\sigma}_1$ and $\vec{\sigma}_2$. If measurement of the component $\vec{\sigma}_1 \cdot \vec{a}$, where $\vec{a}$ is some unit vector, yields the value $+1$ then, according to quantum mechanics, measurement of $\vec{\sigma}_2 \cdot \vec{a}$ must yield the value -1 and vice versa. Now we make the hypothesis [2], and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other. Since we can predict in advance the result of measuring any chosen component of $\vec{\sigma}_2$, by previously measuring the same component of $\vec{\sigma}_1$, it follows that the result of any such measurement must actually be predetermined. Since the initial quantum mechanical wave function does *not* determine the result of an individual measurement, this predetermination implies the possibility of a more complete specification of the state.

J. Bell, Physics 1, 195 (1964)

EPR Paradox

Einstein-Podolsky-Rosen (1935): Quantum theory is not complete!

“While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible.”

(Einstein, Podolsky, Rosen:‚Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?‘ – Phys. Rev. 47, 777 (1935)

John Bell : Such a (local hidden-variable) theory is not possible!

(Physics 1, 195 (1964)