Interaction-Free Ion-Photon Gates

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Early Interaction-Free Experiments

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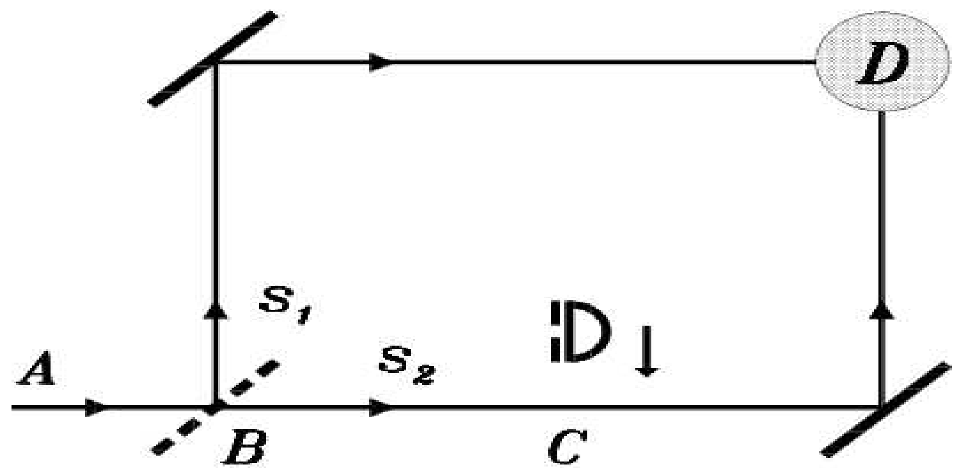

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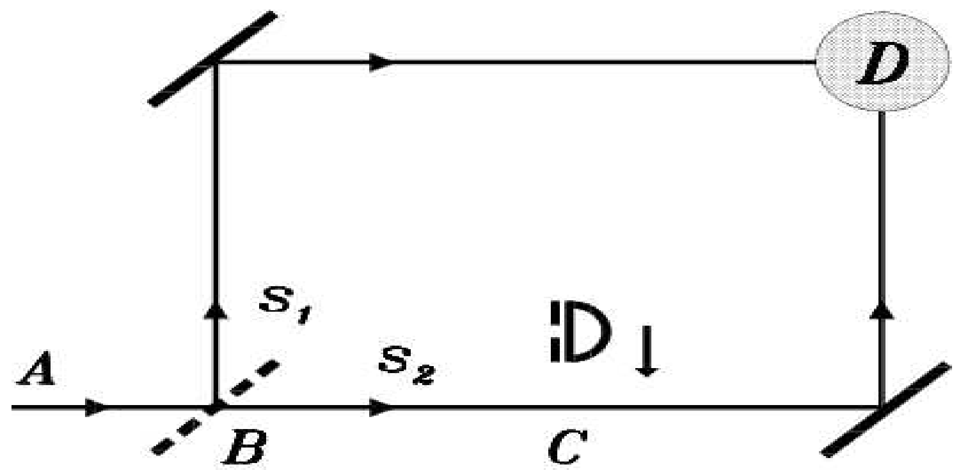

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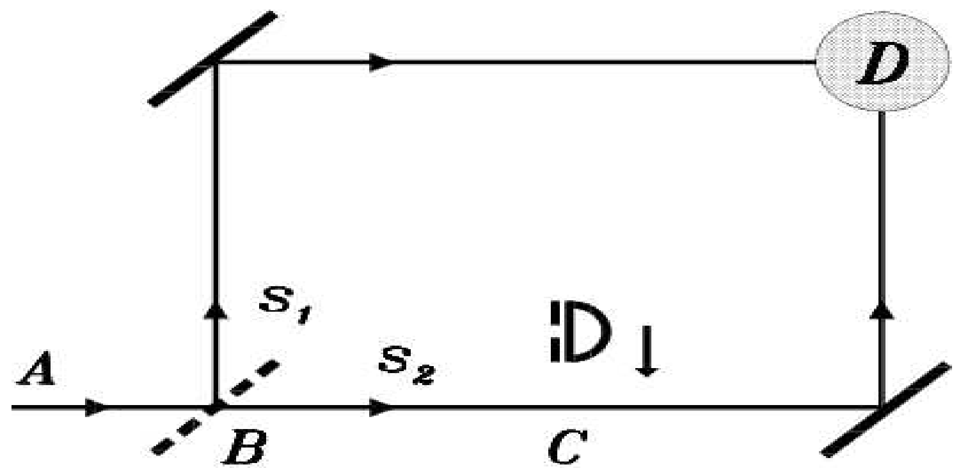

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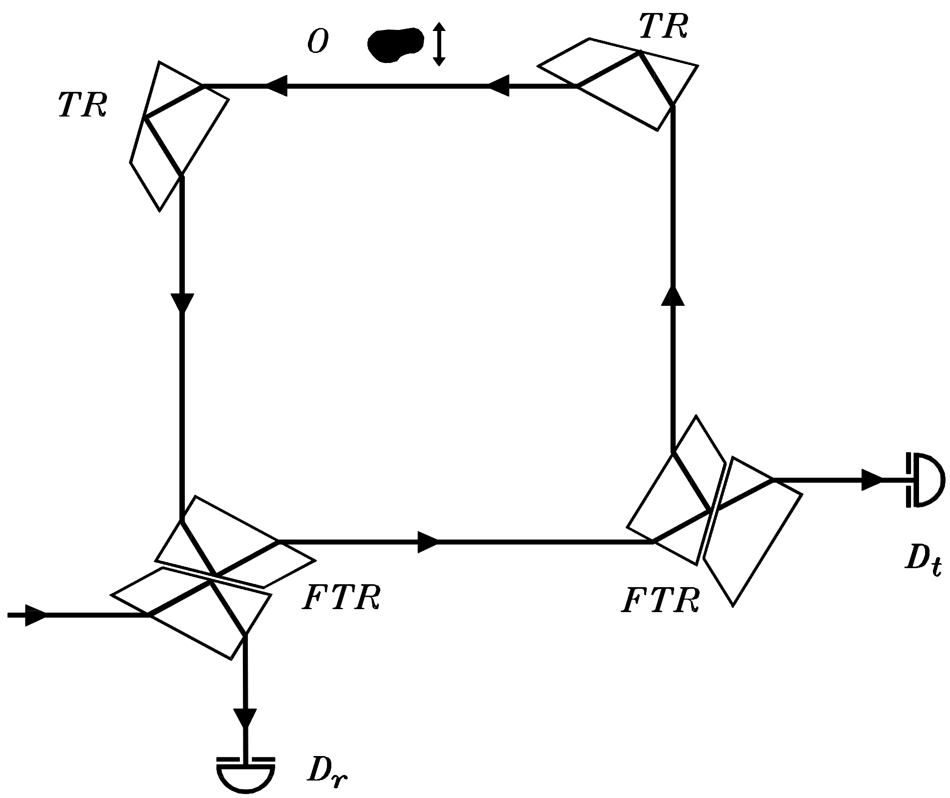

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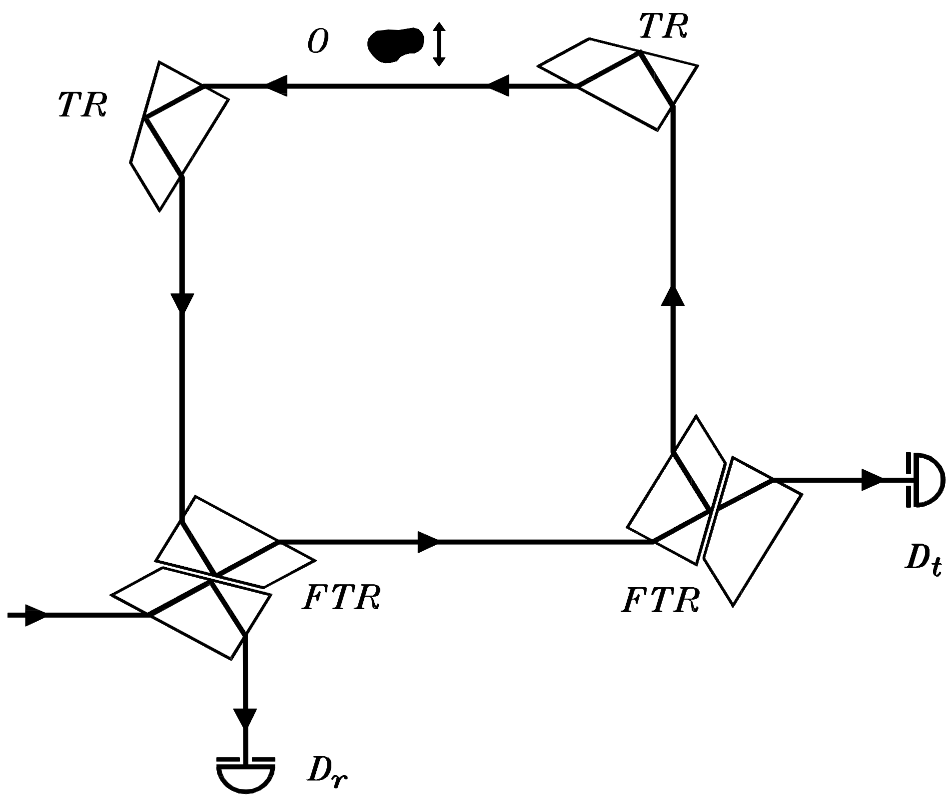

Let us calculate what we get at D_r:

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Reflected portion of the incoming beam:

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"All" round trips: interference (a geometric progression) — the total amplitude (D_r):

$$B = \sum_{i=0}^{\infty} B_i = -A\sqrt{R}\frac{1-e^{i\psi}}{1-R\,e^{i\psi}}$$

Resonator Int.-Free Experiments

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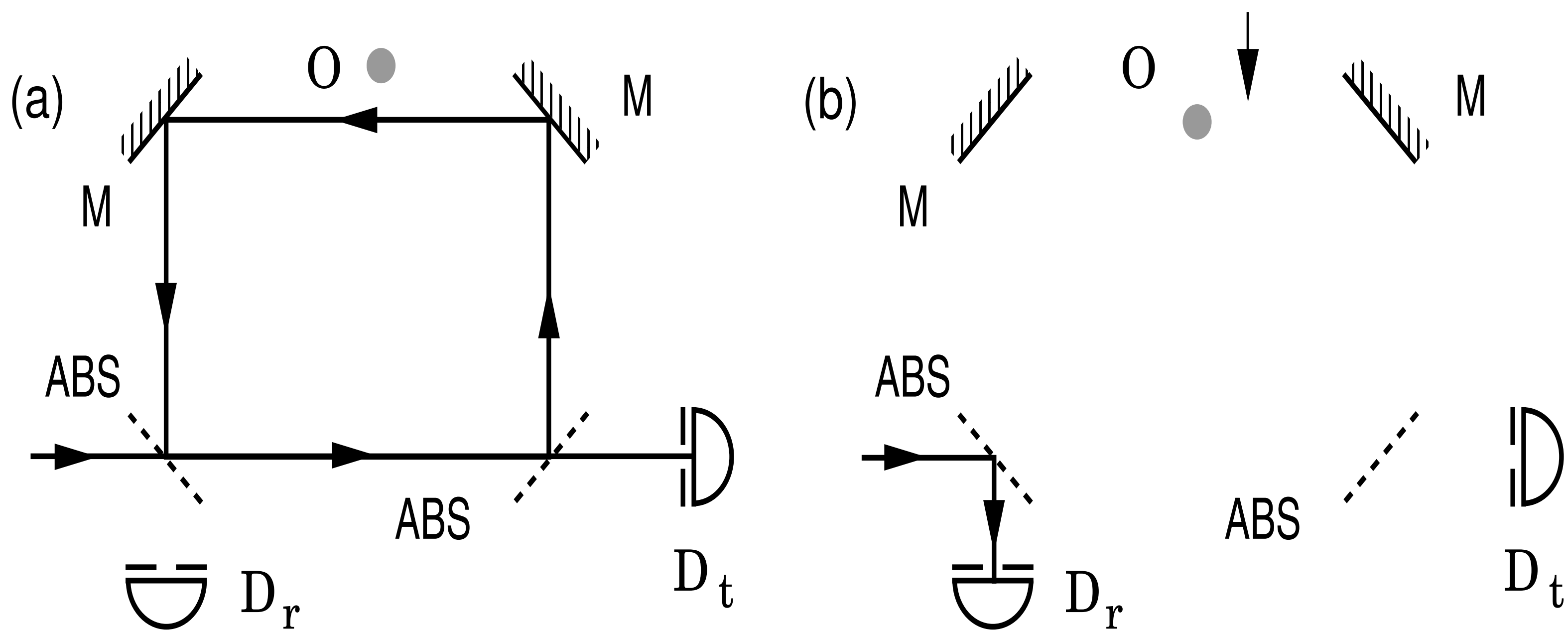
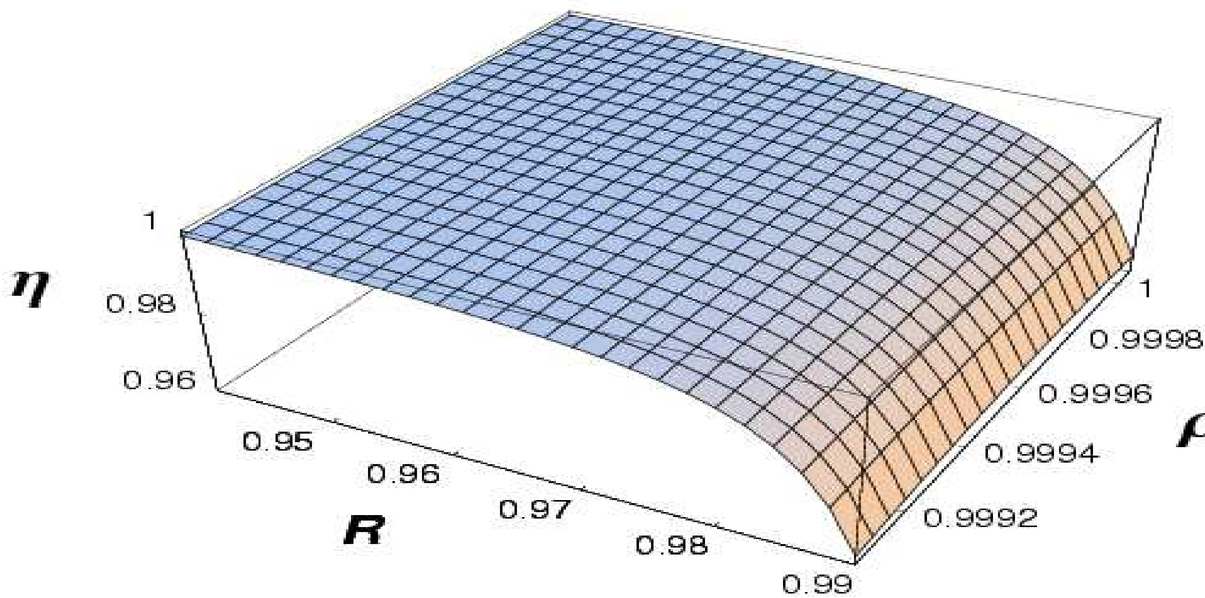


Classical Efficiency



The efficiency of the suppression of the reflection into D_r when there is no object in the resonator; ρ is the measure of losses

Let object be atom

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External magnetic field $\mathbf{B}$ splits the levels into magnetic Zeeman sublevels: $m = -F, -F + 1, \ldots, F$.

Atom vs. photon

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When a photon is emitted, the same selection rules must be observed.

Atom vs. photon (ctnd.)

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we arrive at the Hamiltonian

$$\hat{H} = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1(t) & 0 \\ \Omega_1(t) & 2\Delta & \Omega_2(t) \\ 0 & \Omega_2(t) & 0 \end{bmatrix}$$

Ω_1 and Ω_2 are Rabi frequencies

Excited state drops out

One of the eigenstates of the Hamiltonian is

$$|\Psi^0\rangle = \frac{1}{\sqrt{\Omega_1^2(t) + \Omega_2^2(t)}} (\Omega_2(t)|g_1\rangle - \Omega_1(t)|g_2\rangle)$$

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We can use this to obtain a direct transfer of electrons from $|g_1\rangle$ to $|g_2\rangle$ without either emitting or absorbing photons on the part of atom in the following way—*Stimulated Raman adiabatic passage* (STIRAP).

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Experimentally, let photons be laser beams.

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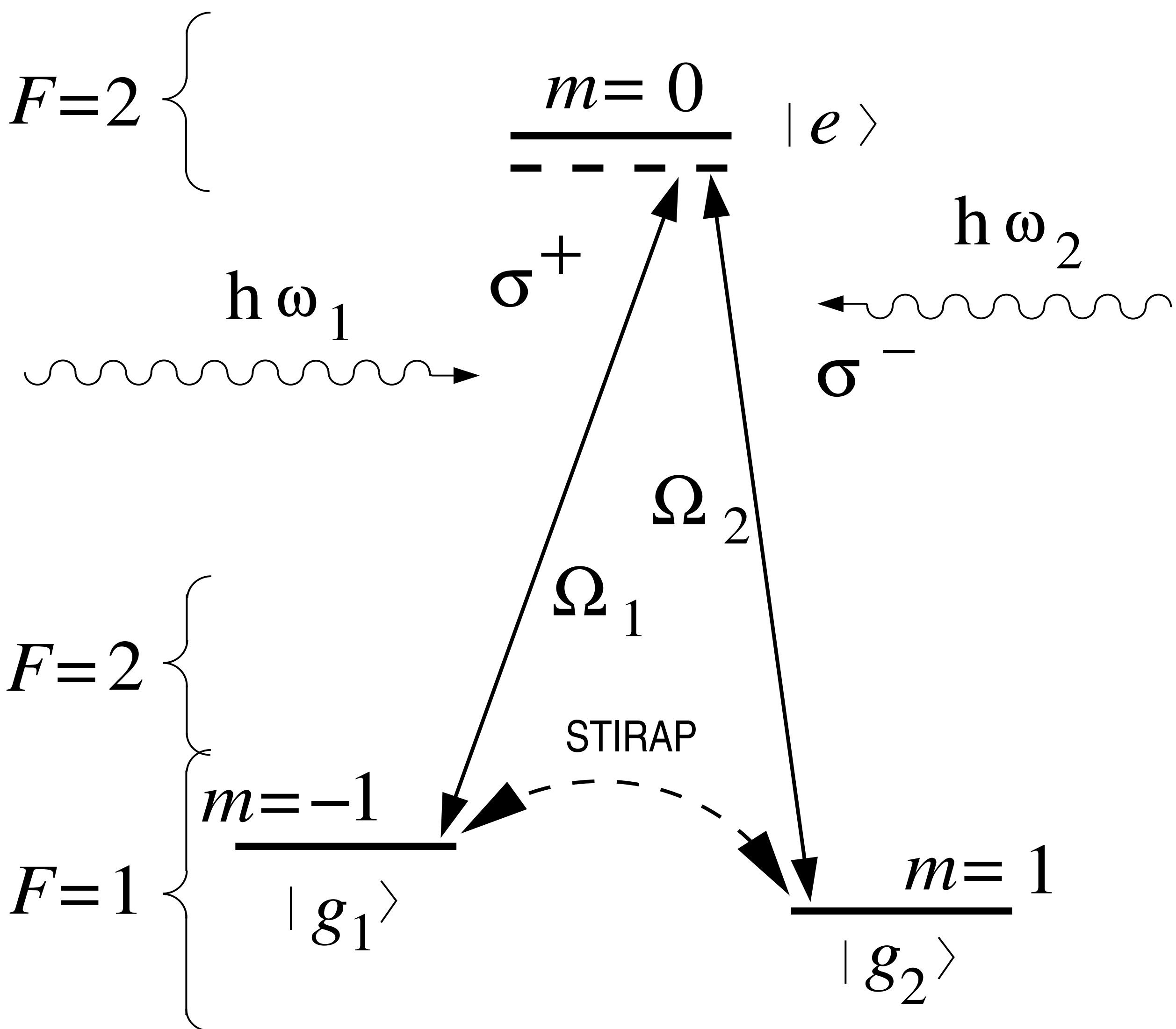
This can be described by

$$\left|\langle g_1|\Psi^0\rangle\right|^2 = 1 \quad \text{for} \quad t \to -\infty$$

$$\left|\langle g_2|\Psi^0\rangle\right|^2 = 1 \quad \text{for} \quad t \to +\infty$$

Adiabatic complete population transfer $|g_1\rangle \to |g_2\rangle$ is STIRAP:

STIRAP $|g_1\rangle \leftrightarrow |g_2\rangle$



Interaction-free “excitation”

A left-hand circularly polarized photon *could* excite an atom from its ground state $|g_1\rangle$ to its excited state $|e\rangle$ and a right-hand circularly polarized photon *could* excite the atom from $|g_2\rangle$ to $|e\rangle$.

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We can induce a change of the atom from $|g_1\rangle$ to $|g_2\rangle$ and back by a STIRAP process, with two additional external laser beams

State notation

We feed our resonator with $+45^\circ$ and -45° linearly polarized photons.

In front of an atom we place a quarter-wave plate (QWP) to turn a 45°-photon into an R-photon and a -45°-photon into an L-photon.

Behind the atom we place a half-wave plate (HWP) to change the direction of the circular polarization and then another QWP to transform the polarization back into the original linear polarization.

State notation (ctnd.)

We denote the atom states as follows:

$$|0\rangle = |g_1\rangle, \qquad |1\rangle = |g_2\rangle$$

They are control states; atom is control qubit.

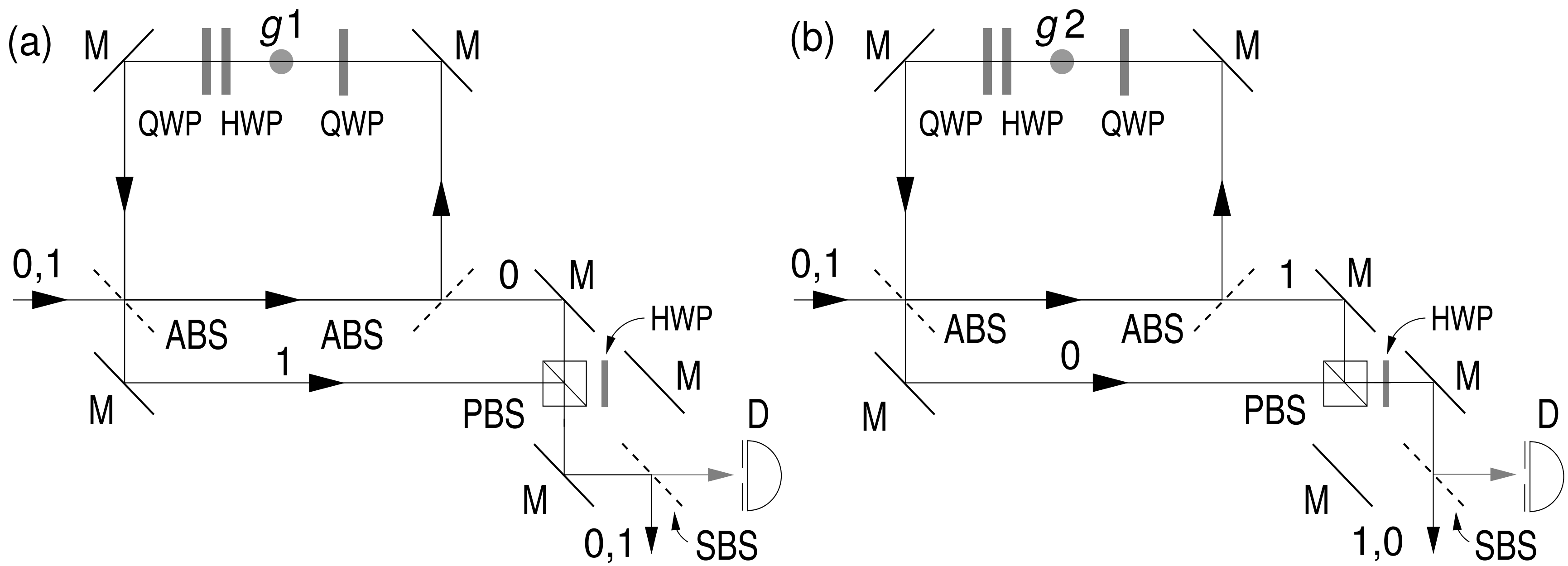
We denote the photon states as follows:

$$|0\rangle = |45^\circ\rangle, \qquad |1\rangle = |-45^\circ\rangle$$

They are target states; photons are target qubits.

For example, $|01\rangle$ means that the atom is in state $|g_1\rangle$ and the photon is polarized along -45°.

Interaction-free CNOT gate



(a) The atom is in state $|g_1\rangle$ and can absorb $|1\rangle$;
(b) The atom is in state $|g_2\rangle$ and can absorb $|0\rangle$;

$$|00\rangle \to |00\rangle, \ |01\rangle \to |01\rangle, \ |10\rangle \to |11\rangle, \ |11\rangle \to |10\rangle$$