Kako foton zna kud treba ići?

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MZOS projekti

Kvantno računanje: paralelizam i vizualizacija

(082-0982562-3160)

Voditelj: Mladen Pavičić, suradnici: Danko Bosanac i Krešimir Fresl

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Eksperimentalne tehnike kvantne komunikacije i kvantne informatike

(098-0352851-2873)

Voditelj: Mario Stipčević, suradnici: Branka Medved, Hrvoje Skenderović i Mladen Pavičić

Kvantni kompjutori: dostignuća i planovi

LA-UR-04-1778

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

**Report of the
Quantum Information Science and Technology
Experts Panel**

Implementacije

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkabilit	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟠	🟠	🟢	🟠	🔴	🔴
Trapped Ion	🟠	🟢	🟠	🟢	🟢	🟠	🟠
Neutral Atom	🟠	🟢	🟠	🟠	🟠	🟠	🟠
Cavity QED	🟠	🟢	🟠	🟠	🟢	🟠	🟠
Optical	🟠	🟠	🟢	🟠	🟠	🟠	🟢
Solid State	🟠	🟠	🟠	🟠	🟠	🔴	🔴
Superconducting	🟠	🟢	🟠	🟠	🟠	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟠 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

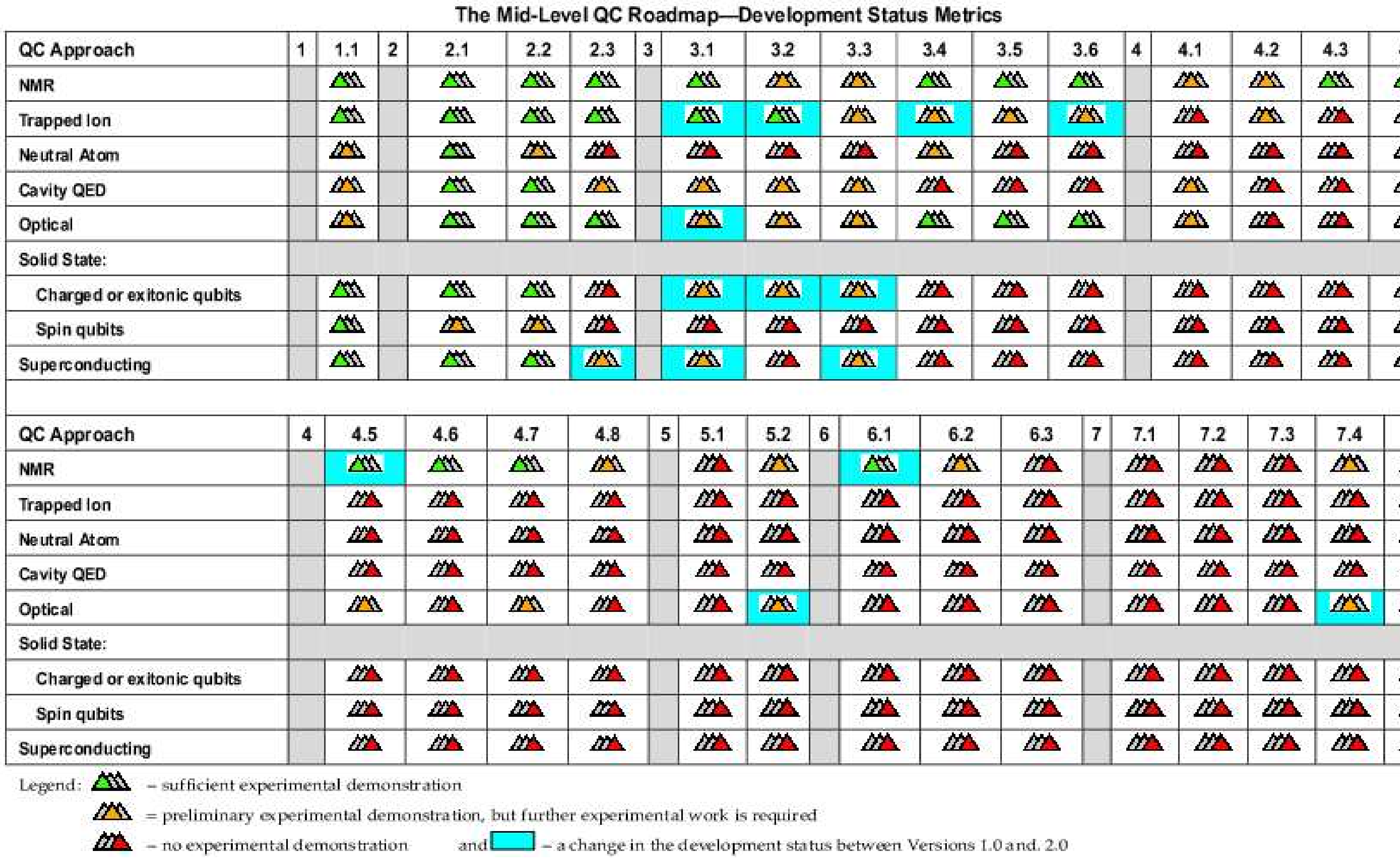
#4. A universal set of quantum gates.

#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

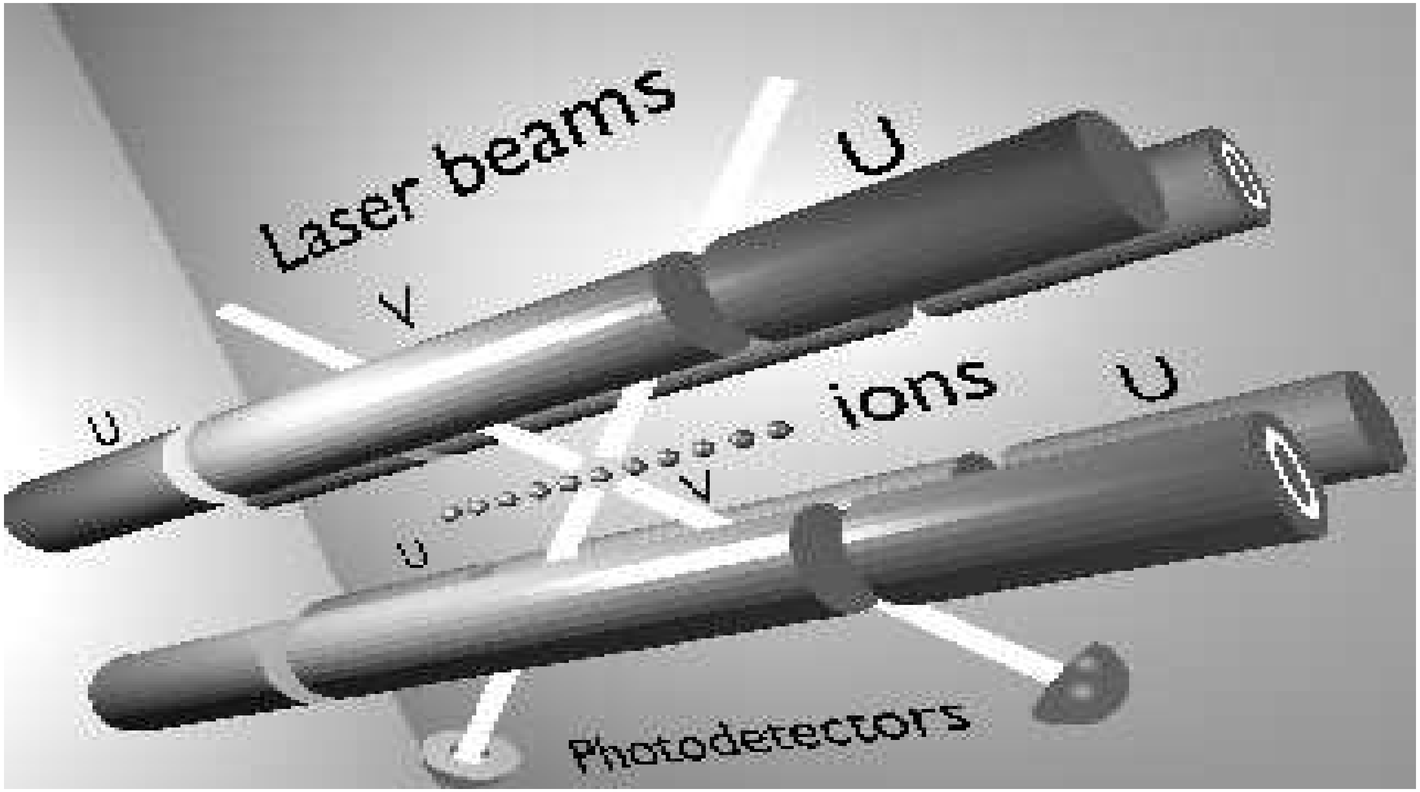
Uspjesi


The Mid-Level QC Roadmap—Development Status Metrics
QC Approach
1 1.1 2 2.1 2.2 2.3 3 3.1 3.2 3.3 3.4 3.5 3.6 4 4.1 4.2 4.3
NMR
Trapped Ion
Neutral Atom
Cavity QED
Optical
Solid State:
Charged or exitonic qubits
Spin qubits
Superconducting
QC Approach
4 4.5 4.6 4.7 4.8 5 5.1 5.2 6 6.1 6.2 6.3 7 7.1 7.2 7.3 7.4
NMR
Trapped Ion
Neutral Atom
Cavity QED
Optical
Solid State:
Charged or exitonic qubits
Spin qubits
Superconducting
Legend:
= sufficient experimental demonstration
= preliminary experimental demonstration, but further experimental work is required
= no experimental demonstration
and
= a change in the development status between Versions 1.0 and 2.0

Uspjesi - legenda

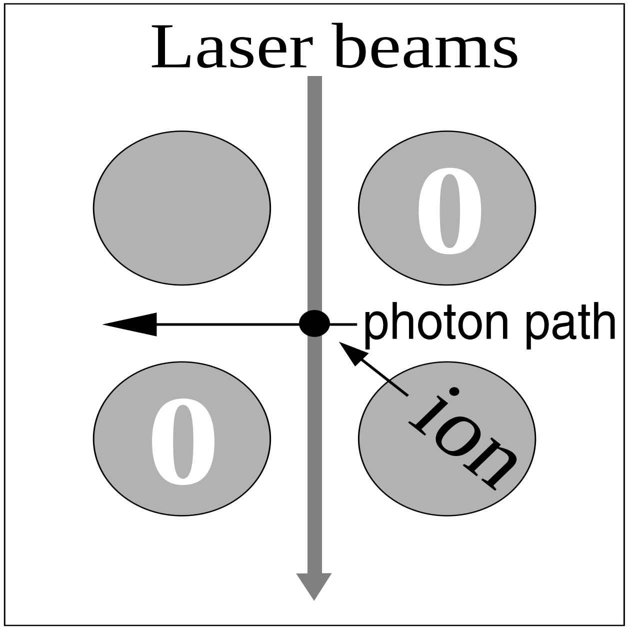
1. Creation of a qubit
   1.1 Demonstrate preparation and readout of both qubit states.
2. Single-qubit operations
   2.1 Demonstrate Rabi flops of a qubit.
   2.2 Demonstrate decoherence times much longer than the Rabi oscillation period.
   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.
3. Two-qubit operations
   3.1 Implement coherent two-qubit quantum logic operations.
   3.2 Produce and characterize the Bell entangled states.
   3.3 Demonstrate decoherence times much longer than two-qubit gate times.
   3.4 Demonstrate quantum state and process tomography for two qubits.
   3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).
   3.6 Demonstrate a two-qubit quantum algorithm.
4. Operations on 3–10 physical qubits
   4.1 Produce a Greenberger, Horne, and Zeilinger (GHZ) entangled state of three physical qubits.
   4.2 Produce maximally-entangled states of four or more physical qubits.
   4.3 Quantum state and process tomography.
   4.4 Demonstrate DFSs.
   4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multip SWAP operations etc.) between physical qubits.
   4.6 Demonstrate quantum error-correcting codes.
   4.7 Demonstrate simple quantum algorithms (e.g., Deu Josza).
   4.8 Demonstrate quantum logic operations with fault-tolerant precision.
5. Operations on one logical qubit
   5.1 Create a single logical qubit and "keep it alive" usir repetitive error correction.
   5.2 Demonstrate fault-tolerant quantum control of a sir logical qubit.
6. Operations on two logical qubits
   6.1 Implement two-logical-qubit operations.
   6.2 Produce two-logical-qubit Bell states.
   6.3 Demonstrate fault-tolerant two-logical-qubit operat
7. Operations on 3–10 logical qubits
   7.1 Produce a GHZ-state of three logical qubits.
   7.2 Produce maximally-entangled states of four or mor logical qubits.
   7.3 Demonstrate the transfer of quantum information between logical qubits.
   7.4 Demonstrate simple quantum algorithms (e.g., Deu Josza) with logical qubits.
   7.5 Demonstrate fault-tolerant implementation of simp quantum algorithms with logical qubits.

Atom-photon



Mladen Pavičić, Quantum Computation and Quantum Communication: Theory and Experiments, *Springer Verlag*, New York (2005)

Atom-photon path



Mladen Pavičić, Nondestructive interaction-free atom-photon controlled-NOT gate, *Physical Review A*, **75**, 032342-1-8 (2007)

Snop bez fotona

Antikne ideje: Renninger (1960), Dicke (1981), Pavičić (1986)

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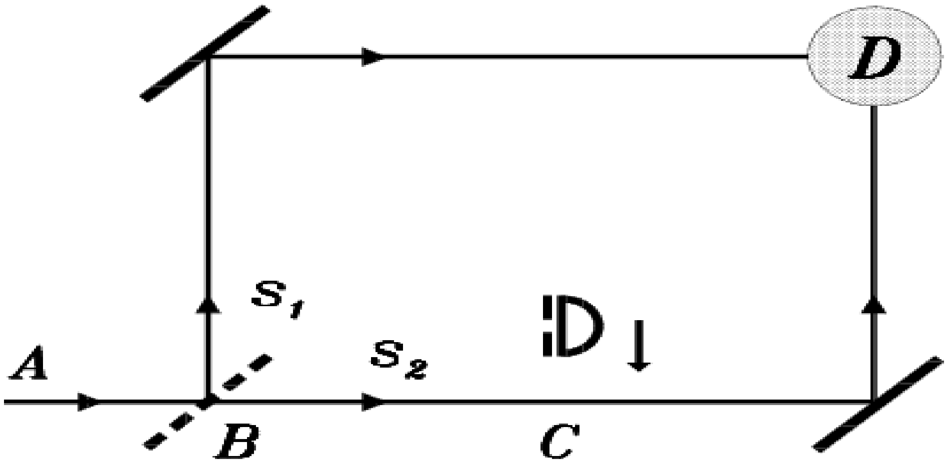


"Kad u *C* ne detektiramo ništa, mi uništavamo interferenciju u *D*." Pavičić, (1986)

Interaction-Free fotoni

1993. ulaze Elitzur and Vaidman:

“Takvo odsutstvo interferencije bi moglo biti korisno”

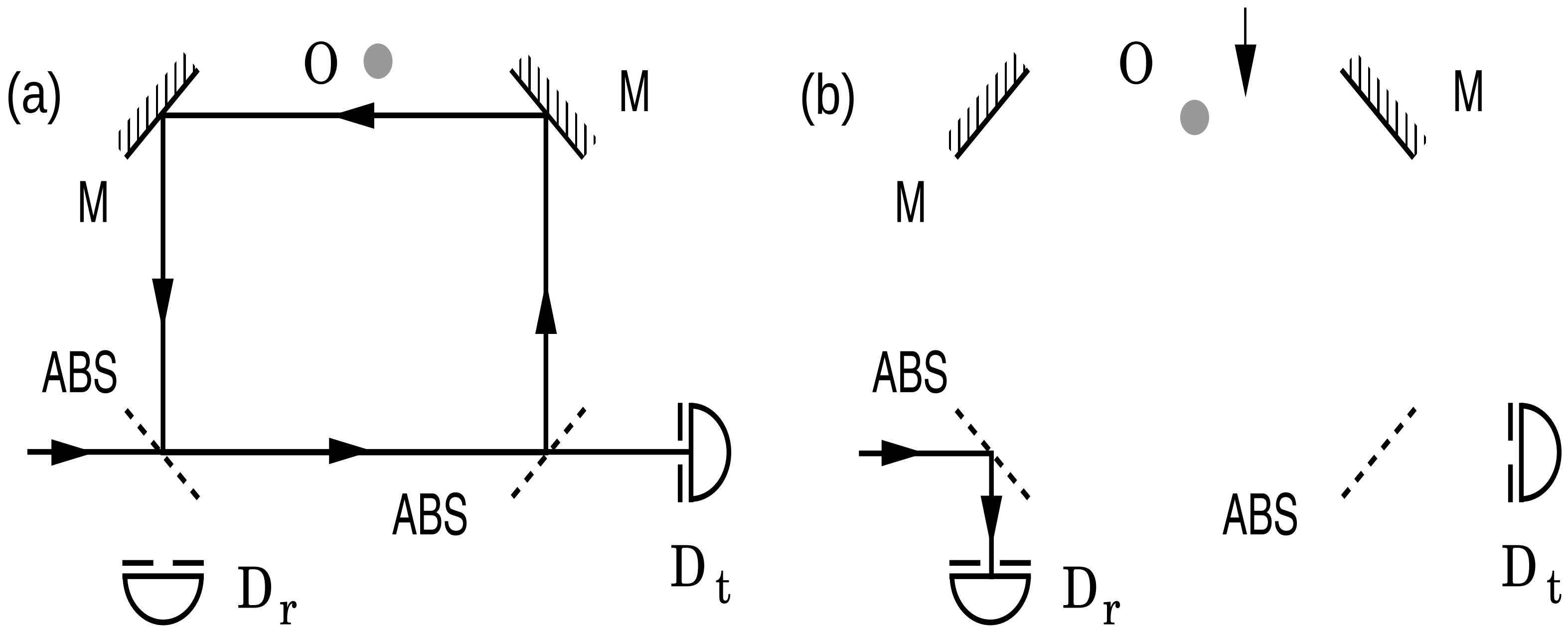
Snop bez fotona

=

Interaction-free fotoni

Prstenasti rezonator

Mladen Pavičić, Resonance Energy-Exchange-Free Detection and 'Welcher Weg' Experiment, *Physics Letters A*, **223**, 241-245 (1996):



Interferencija

Reflektirani dio ulaznog fotonskog snopa (D_r):

$$-B_0 = -A\sqrt{R}$$

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Nakon ∞ obilazaka—interferencija (geometrijska progresija)—ukupna amplituda (za D_r):

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

Eksperiment

$\psi = (\omega - \omega_{res})T$—faza po obilasku; ω—frekvencija ulaznog snopa; T—vrijeme obilaska; ω_{res}—frekvencija rezonancije ($\lambda/2 = L/k$, L—duljina obilaska).

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Čak i za valne pakete—dakle, idealno niti jedan foton ne dolazi u D_r.

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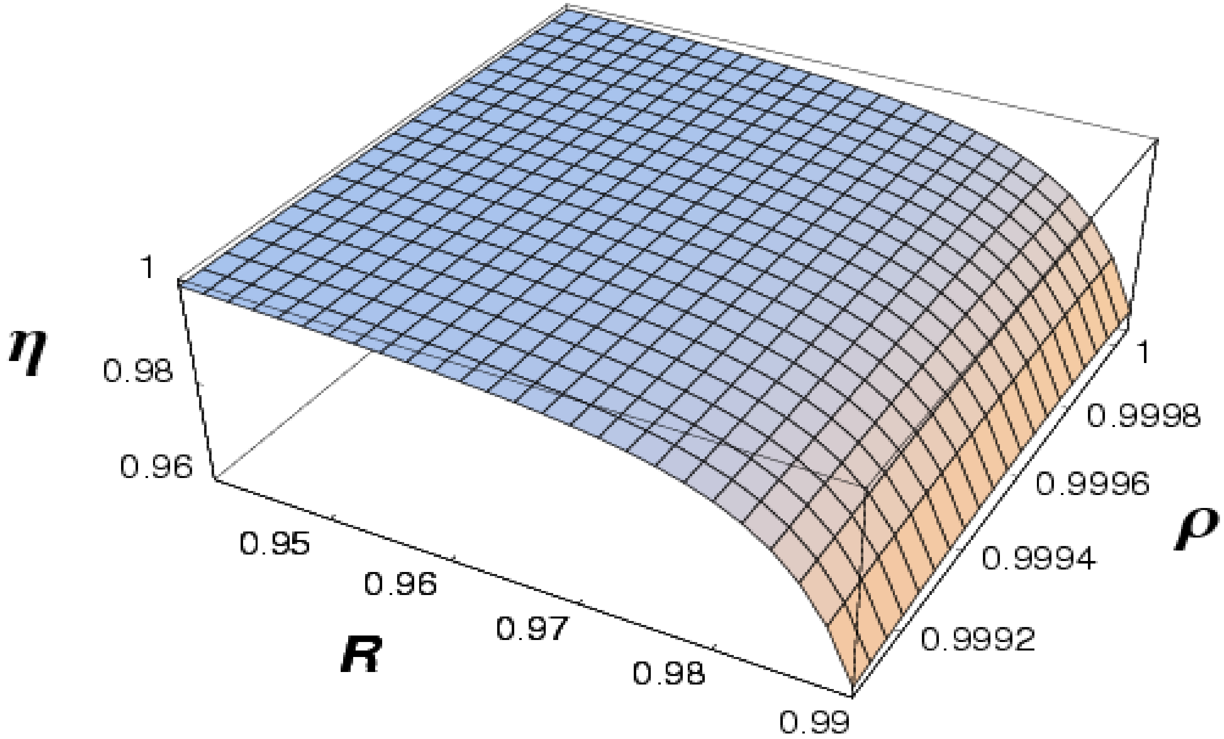
Računanje s valnim paketima pokazuje da se već nakon oko 200 obilazaka efikasnost približava 100%:

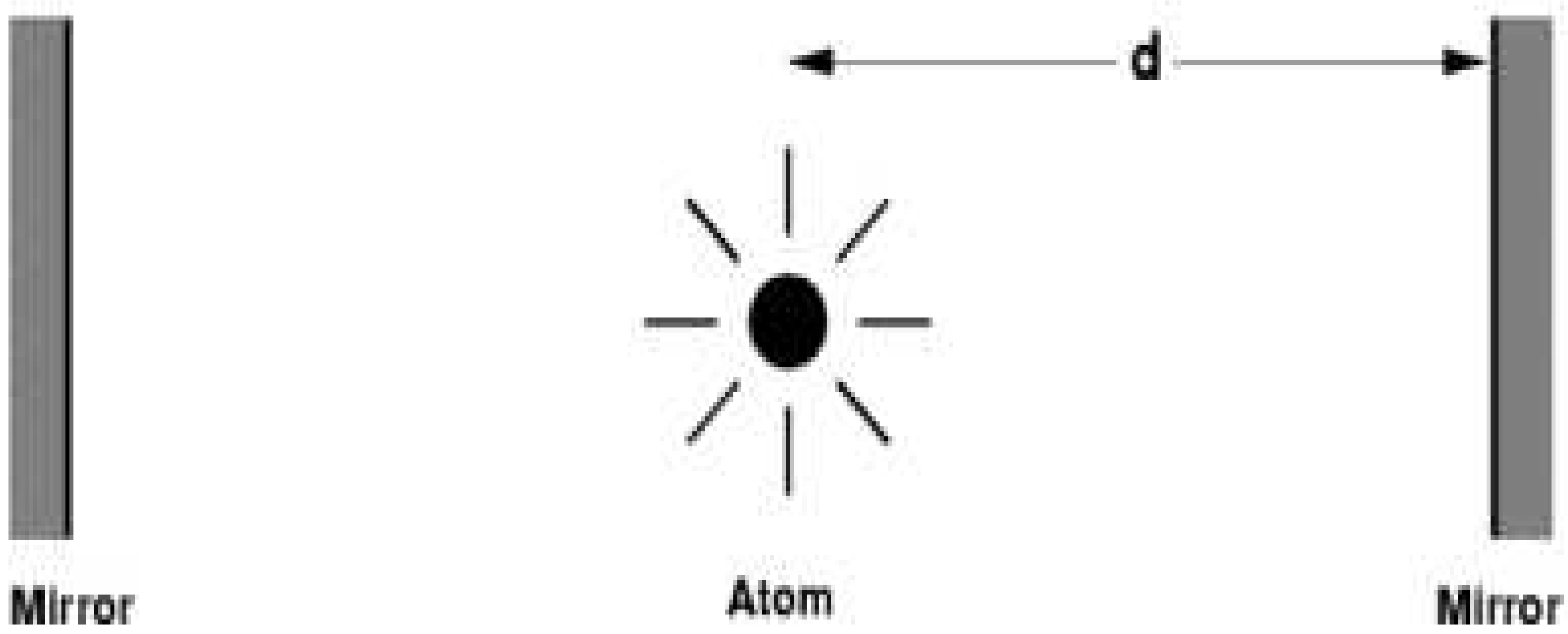
Efikasnost



Efikasnost destruktivne interferencije za D_r kad u rezonatoru nema objekta; ρ je mjera gubitaka.

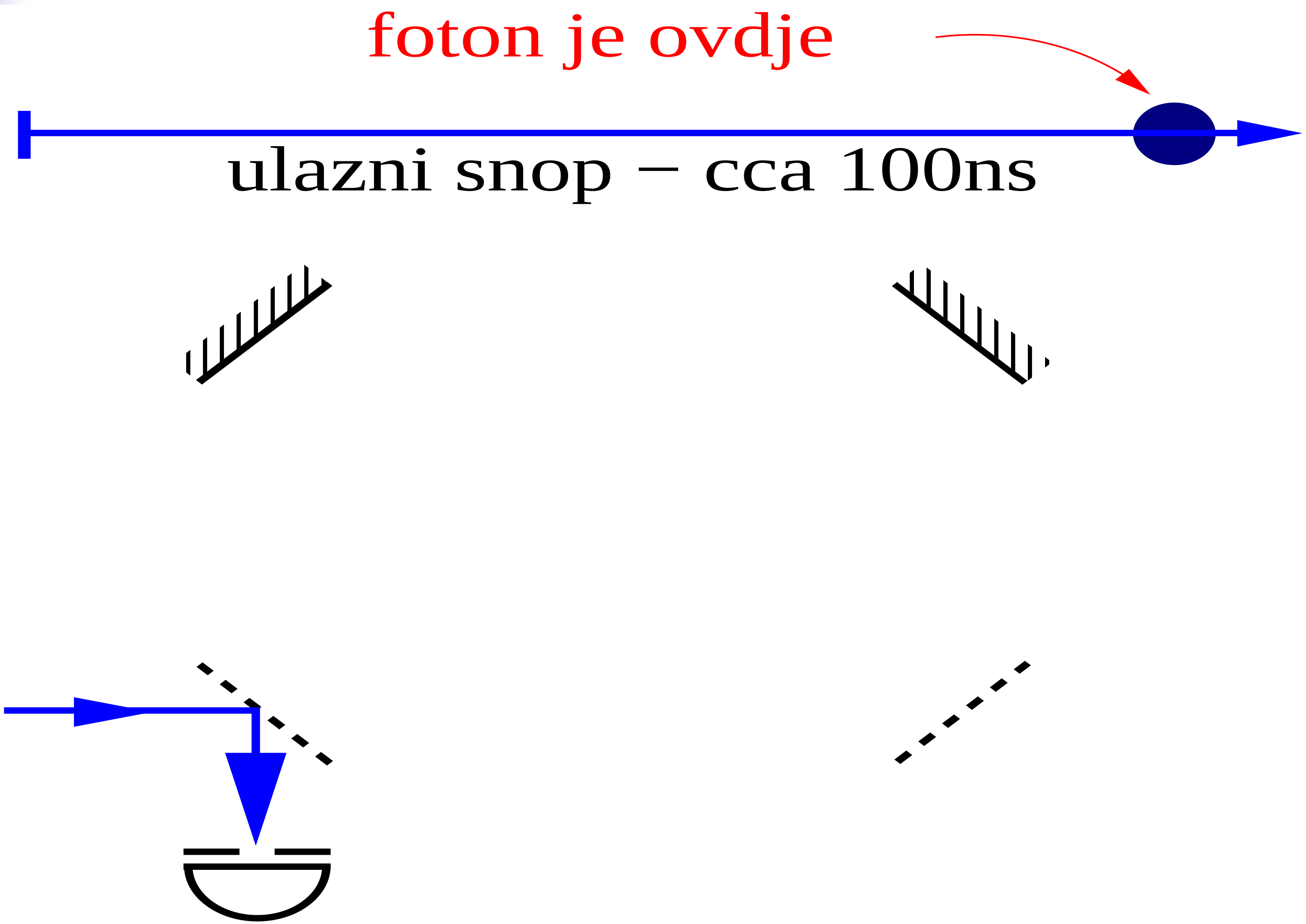
Milonniev eksperiment

H. Fearn, R.J. Cook & P.W. Milonni, *Phys. Rev. Lett.* **74**, 1327 (1995)

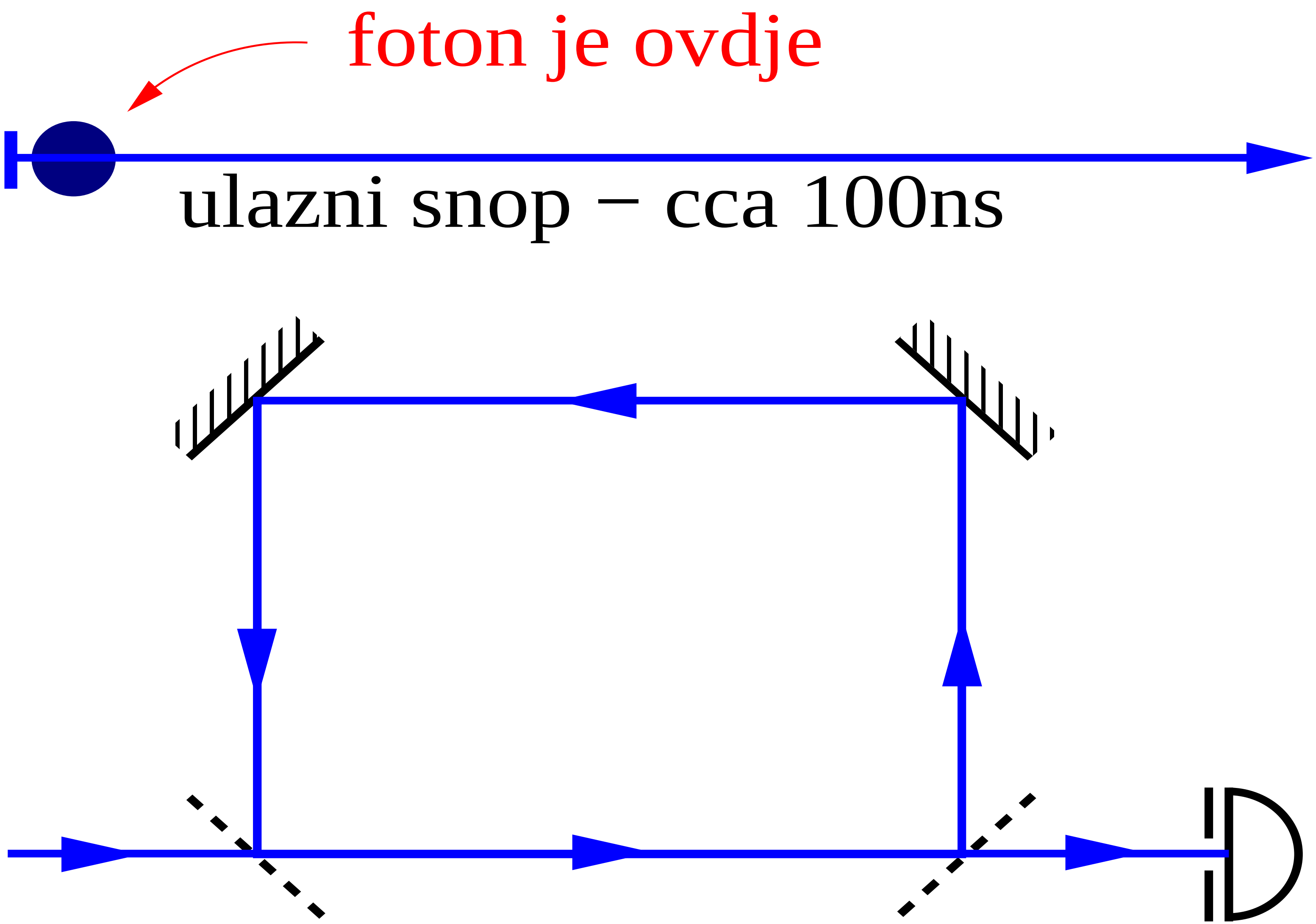


D. Branning, P. Kwiat and A. Migdall, *Proceedings of the 6th Int. Conf. on Quantum Communication, Measurement and Computing*, ed. J. Shapiro & O. Hirota (Rinton Press, New Jersey, 2003), p. 129

Naš eksperiment



Naš eksperiment



Neka je objekt atom

^{87}Rb ima zatvorene ljuske do $4p$ i elektron u osnovnom stanju $5s$ ($\mathbf{J} = \mathbf{L} + \mathbf{S}$); Promatrajmo ekscitirano stanje: $5p_{1/2}$.

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^{87}Rb ima $K = 3/2$, a $j = 1/2$ osnovna stanja su “pocijepana” hiperfinom interakcijom u dublete s $F = K \pm j = 3/2 \pm 1/2 = 2, 1$.

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Vanjsko magnetsko polje $\mathbf{B}$ cijepa nivoe na Zeeman podnivoe: $m = -F, -F+1, \ldots, F$.

Atom vs. foton

Za ekcitaciju i deekscitaciju elektrona izmedju $m = \pm 1$ i $m = 0$ moramo koristiti cirkularno polarizirane fotone sa $j_p = 1$ i $m_{j_p} = \pm 1$

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Kod foton$\rightarrow$atom transfera angularnog momenta, slijedeća selekcijska pravila moraju biti zadovoljena:

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Kod emisije fotona, vrijede jednaka selekcijska pravila.

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Schrödingerova jednadžba za naš sistem je

$$\hat{H}|\Psi\rangle = i\hbar\frac{\partial|\Psi\rangle}{\partial t}\,,$$

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odakle za naš 3-nivoini sistem slijedi 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 su Rabieve frequencije).

Elektron ne “vidi” ekcitirano stanje

Jedno od svojstvenih stanja Hamiltoniana je

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

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Dakle elektroni mogu direktno prelaziti iz $|g_1\rangle$ u $|g_2\rangle$ bez da atom bilo emitira bilo absorbira fotone—*Stimulated Raman adiabatic passage* (STIRAP).

STIRAP

Eksperimentalno, neka su fotoni laserski snopovi.

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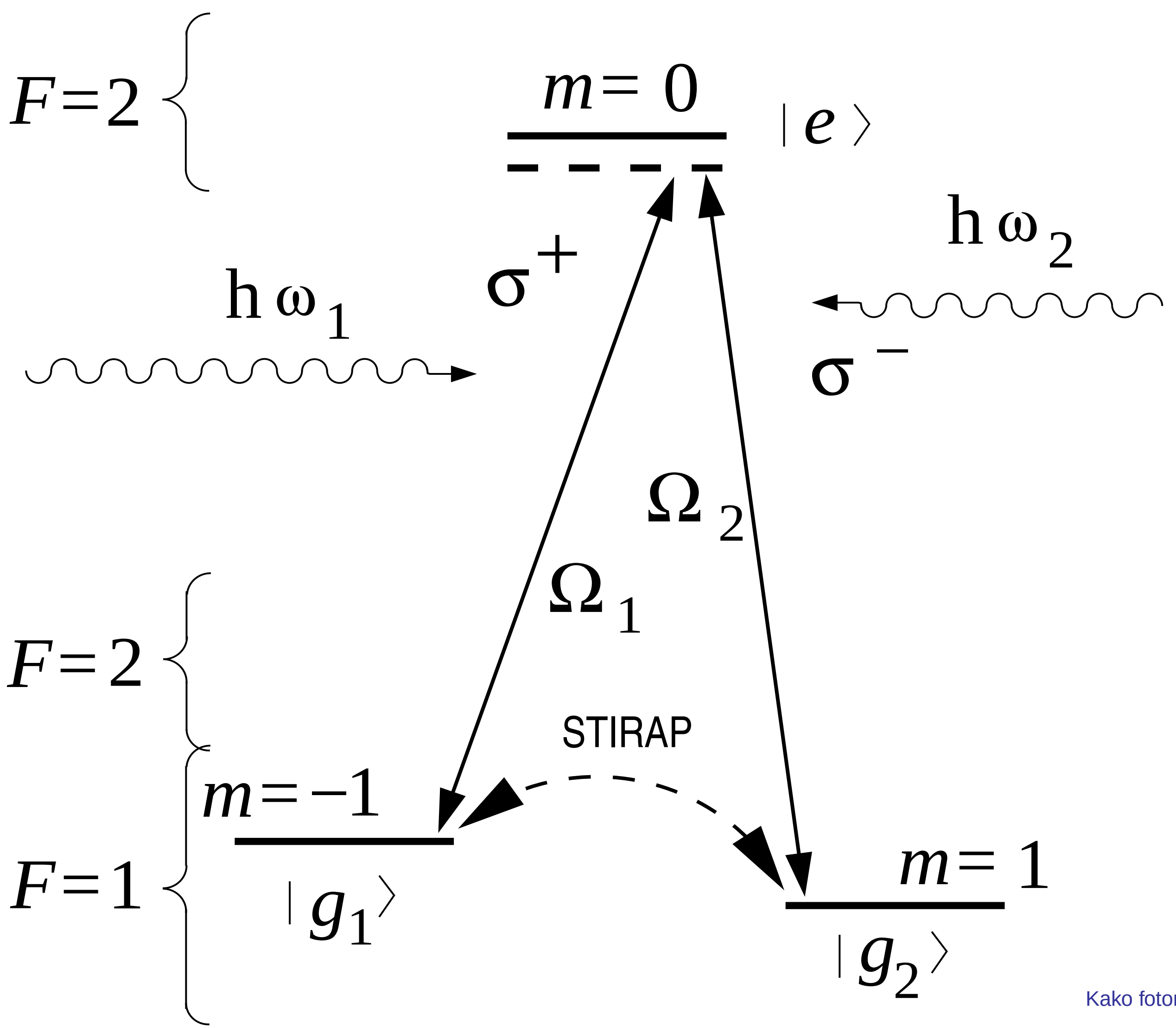
To možemo izraziti kao:

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

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

Taj adijabatski populacijski prijelaz $|g_1\rangle \to |g_2\rangle$ je STIRAP:

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



Interaction-free "ekscitacija"

Lijevo cirkularno polarizirani foton *može* ekscitirati atom iz njegovog osnovnog stanja $|g_1\rangle$ u njegovo ekscitirano stanje $|e\rangle$, a desno cirkularno polarizirani foton *može* ekscitirati atom iz $|g_2\rangle$ u $|e\rangle$.

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Dakle, L-foton će “vidjeti” atom $|g_1\rangle$ stanju, ali ga neće “vidjeti” u $|g_2\rangle$ stanju. S R-fotonom, je obrnuto.

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Mi možemo mijenjati stanje atoma iz $|g_1\rangle$ u $|g_2\rangle$ i natrag STIRAP procesom, pomoću dva dodatna vanjska laserska snopa.

Rezonator

U rezonator šaljemo $+45^\circ$ and -45° linearno polarizirane fotone.

Ispred atoma stavljamo 1/4-λ ploču (QWP) da prebacimo 45°-foton u R-foton i -45°-photon u L-foton.

Iza atoma stavljamo 1/2-λ ploču (HWP) da bismo promijenili smjer cirkularne polarizacije i još jednu QWP da prebacimo polarizaciju natrag u originalnu linearnu polarizaciju.

Notacija stanja

Označimo stanja atoma kao:

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

Ona su “kontrolna stanja”; atom je “kontrolni qubit”.

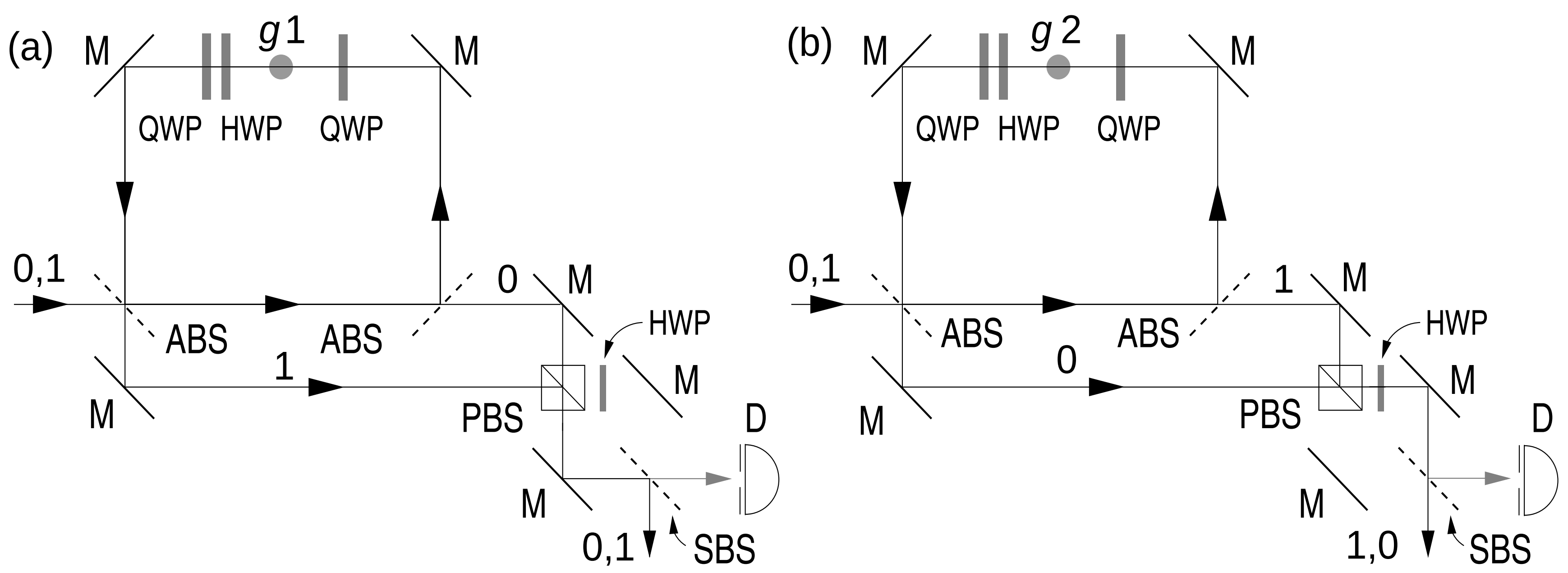
Označimo foton stanja kao:

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

To su “ciljana (target) stanja”; fotoni su “ciljani qubiti”.

Npr., $|01\rangle$ znači da je atom u stanju $|g_1\rangle$, a da je foton polariziran uzduž -45°.

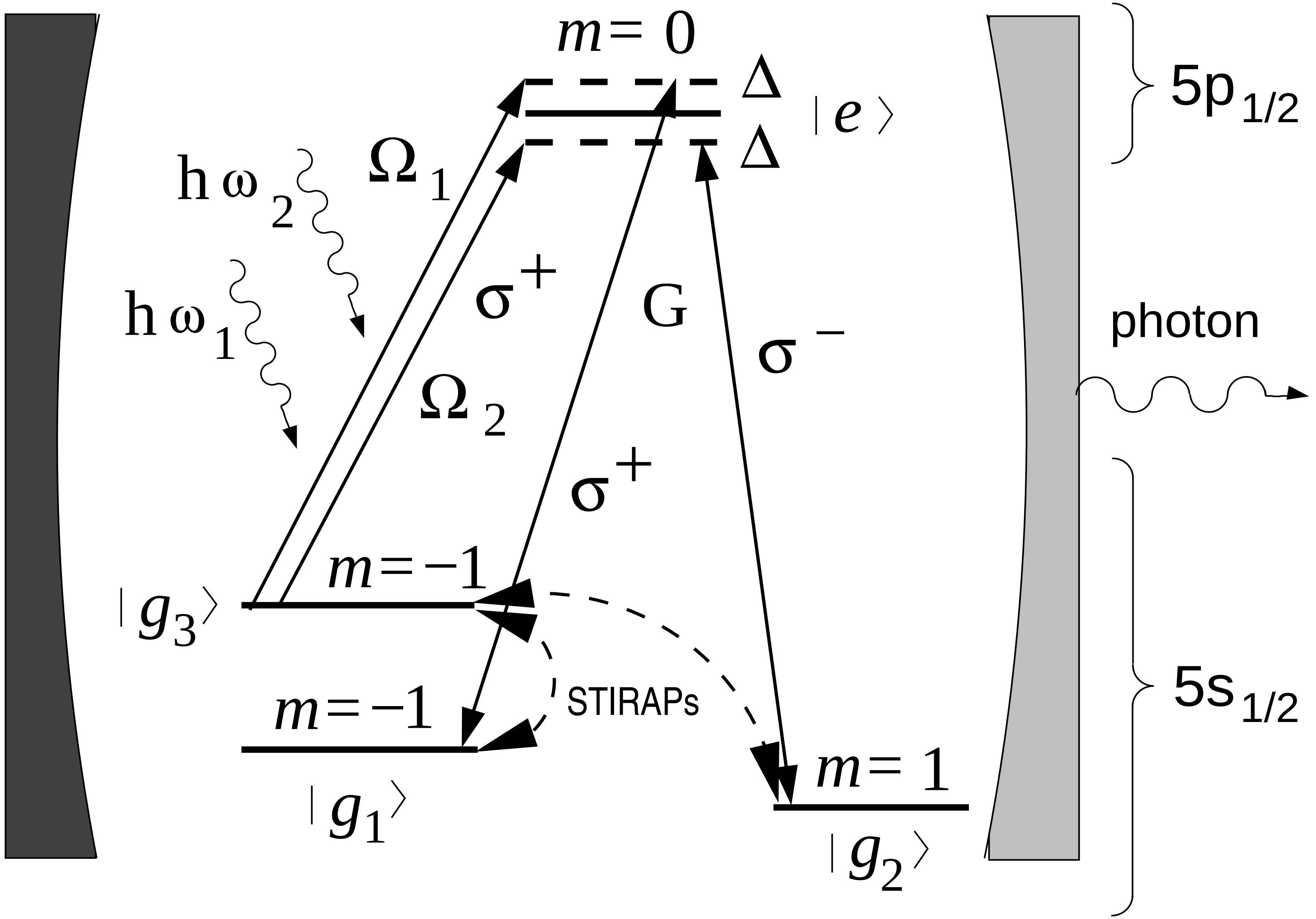
Interaction-free CNOT gate



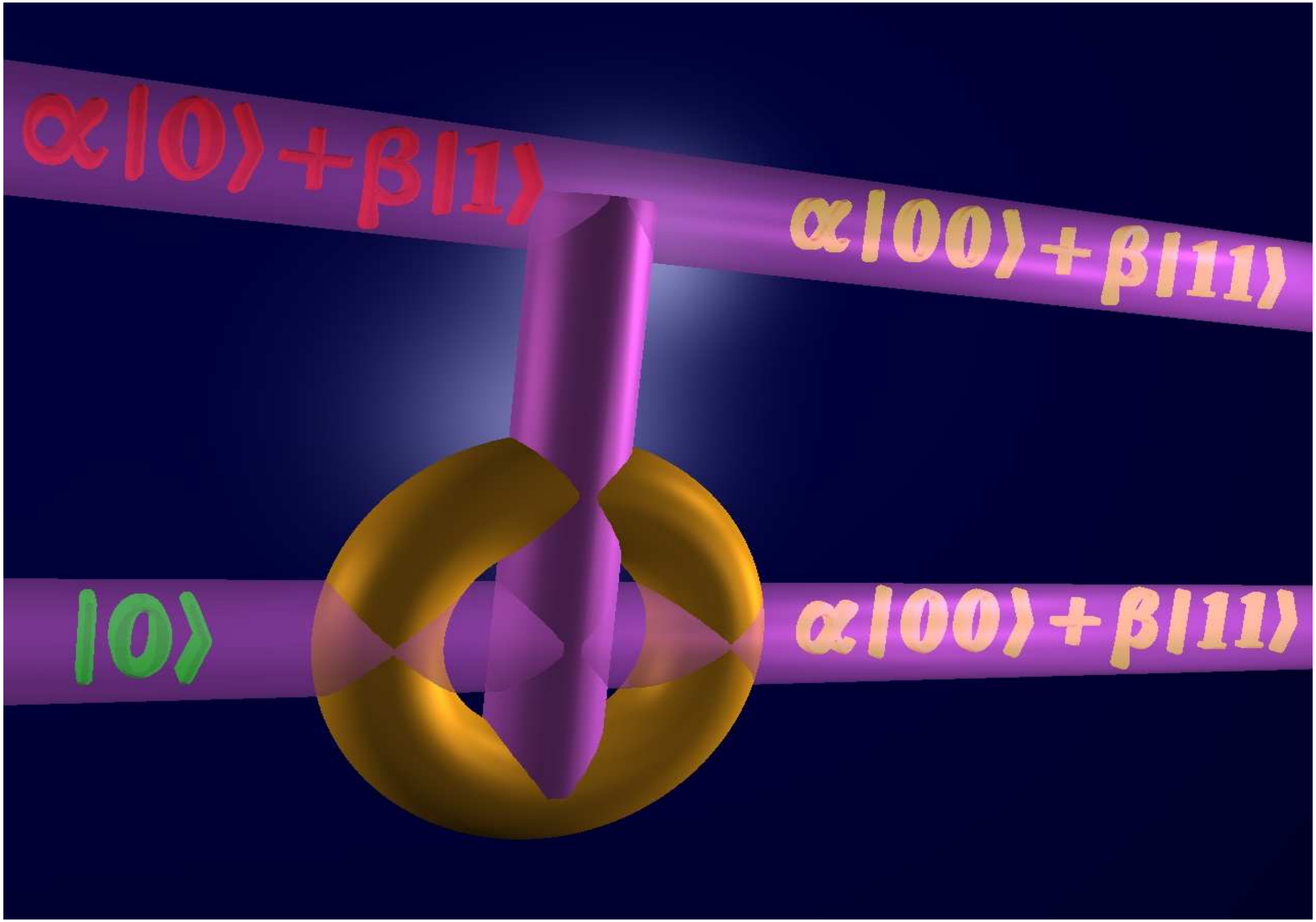
(a) atom je u stanju $|g_1\rangle$ i može absorbirati $|1\rangle$;
(b) atom je u stanju $|g_2\rangle$ i može absorbirati $|0\rangle$;

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

Atom u superpoziji stanja



Spregnuta atom-foton stanja



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Potpisan ugovor po pozivu za

Mladen Pavičić, Companion to Quantum Computation and Communication, John Wiley & Sons & VCH (2009).