Interaction-Free Ion-Photon Quantum CNOT Gates

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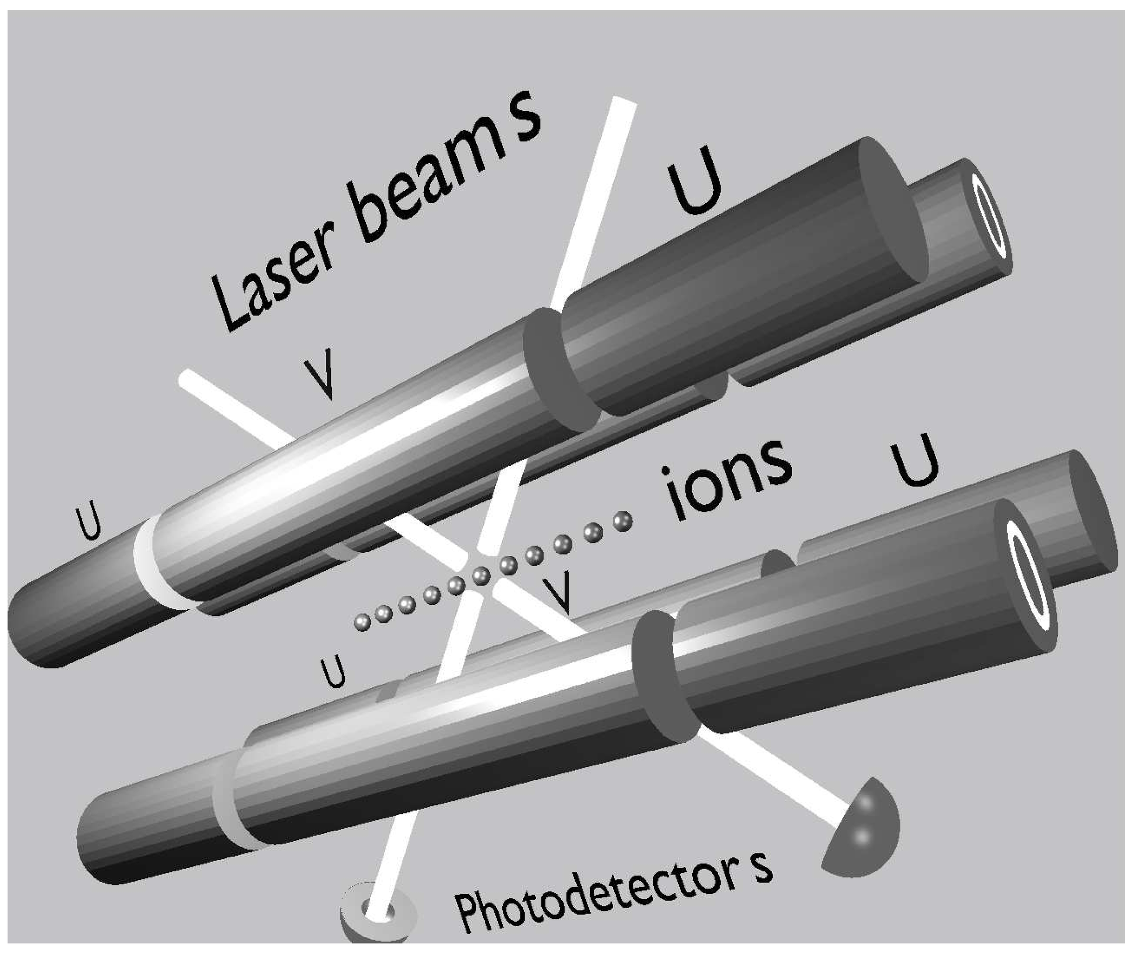
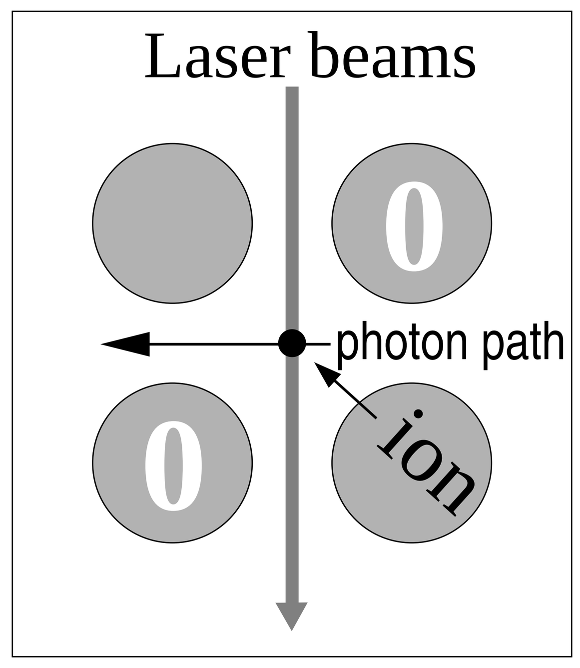
Can we achieve strong coupling of atoms and photons so as to form a controlled-NOT gate without transferring any energy to each other?

Yes! In 2007 [1] we designed nondestructive interaction-free atom-photon controlled-NOT gate where *nondestructive* means that all four outgoing target photon modes of the gate are available and feed-forwardable. We succeeded in making the gate non-destructive by using the ring resonator with two photon outputs. Individual atoms are controlled by a STIRAP transition and photons by a ring resonator with two outgoing ports. Realistic estimates we obtain for ions confined in a Paul trap around which the resonator is mounted show that a strong atom-photon coupling can be achieved. It is also shown how the resonator can be used for controlling superposition of atom states.

When a photon goes through a region in which we put ions—in an ion trap shown in Fig. 1—it will "see" the ion only if it can excite it, i.e, only if the ion can absorb it. So a photon passing through a resonator tuned to a frequency that can excite either $|0\rangle = 3D_{3/2} - 3/2$ or $|1\rangle = 3D_{5/2}1/2$ state depending on its polarization. The beauty of the design is that in reality it will excite neither—it will only exit through one or the other port depending on which state the atom is in.





Laser beams carry out the STIRAP; Photon path is of the ring resonator.

Figure 1. Paul's linear ion trap.

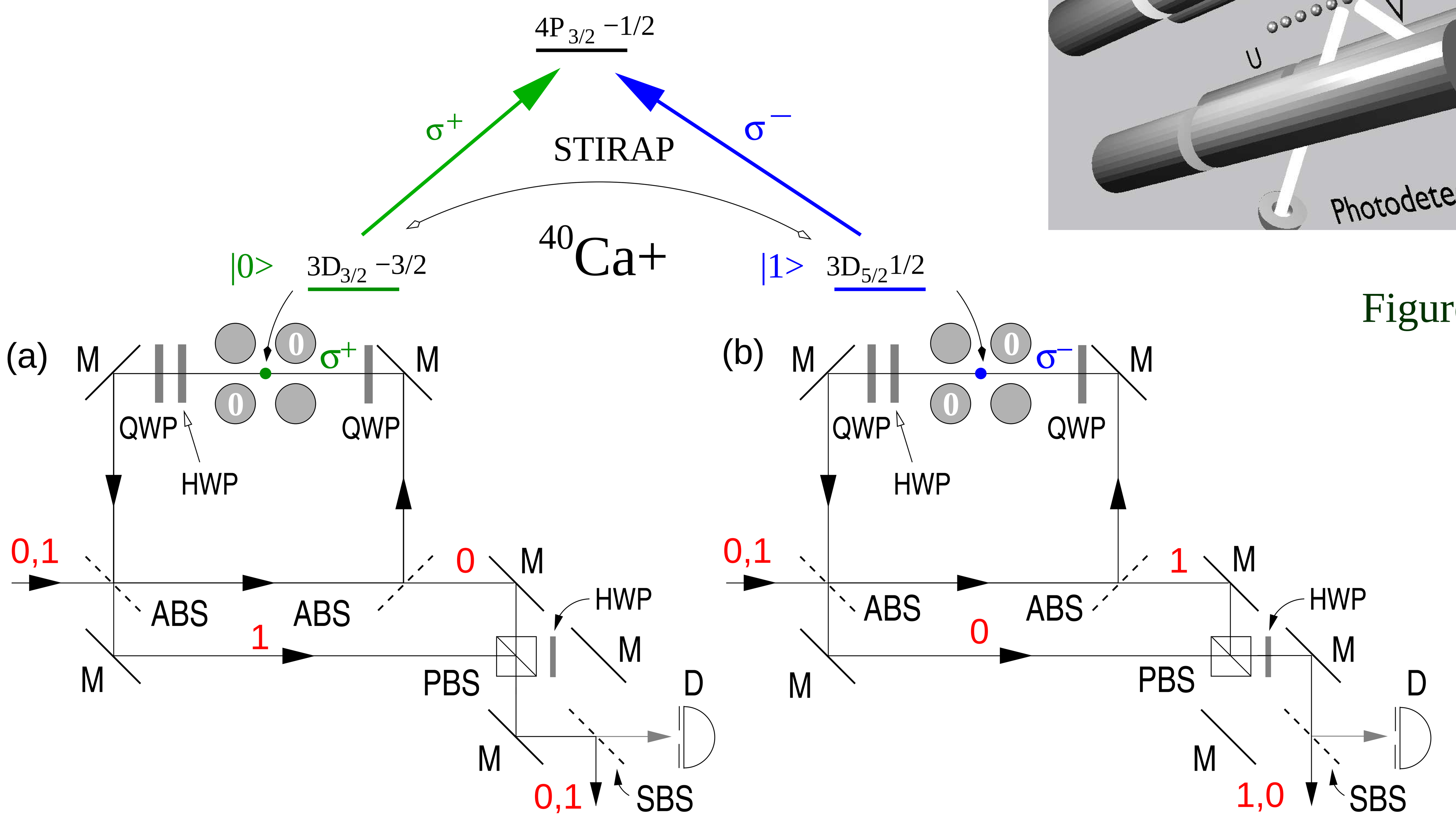


Figure 2: (a) The atom is in state $|0\rangle = 3D_{3/2} - 3/2$ and can absorb σ^+ photon that enters the resonator as -45° polarized photon $|1\rangle$ Therefore a photon in state $|1\rangle$ cannot enter the cavity and thus $|0\rangle \rightarrow |0\rangle$ and $|1\rangle \rightarrow |1\rangle$. (b) The atom is in state $|1\rangle = 3D_{5/2}1/2$ and can absorb a $+45^\circ$ polarized photon $|0\rangle$. Therefore photon $|0\rangle$ cannot enter the cavity and thus $|0\rangle \rightarrow |1\rangle$ and $|1\rangle \rightarrow |0\rangle$. ABS are highly asymmetrical beam splitters with $R = 0.999$; SBS is a symmetric 50:50 beam splitter; M are perfect mirrors; PBS is a polarizing beam splitter which lets $|0\rangle$ photons through and reflects $|1\rangle$ photons; HWP and QWP are half- and quarter-wave plates, respectively—the plates in the resonator turn linear polarization into circular and back into linear and HWP after PBS turns $|0\rangle$ ($|1\rangle$) photon into $|1\rangle$ ($|0\rangle$) photon; D is a detector—ideally, when it does not click, the target qubit exits at the other side of SMS. The obtained CNOT is shown in Fig. 3.

Figure 3. CNOT: $|00\rangle \rightarrow |00\rangle$, $|01\rangle \rightarrow |01\rangle$, $|10\rangle \rightarrow |11\rangle$, $|11\rangle \rightarrow |10\rangle$

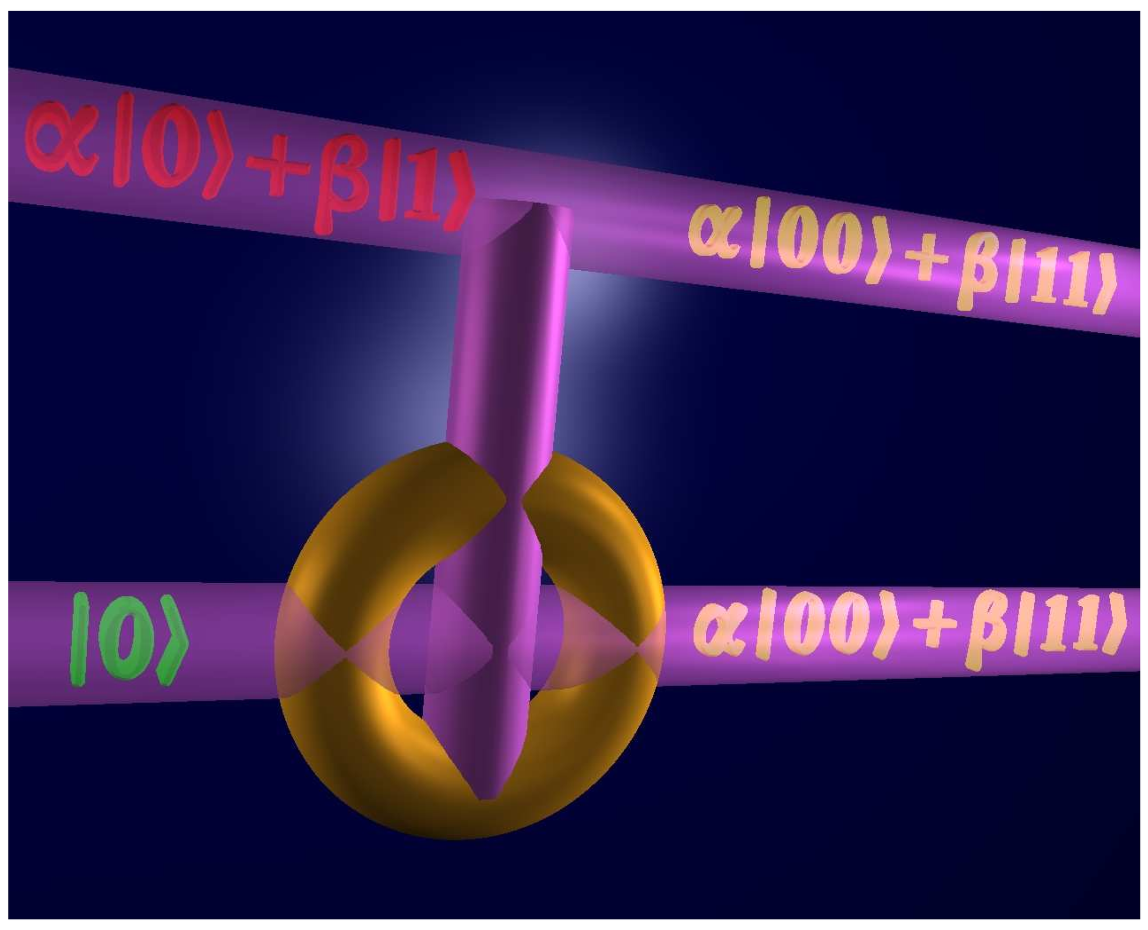
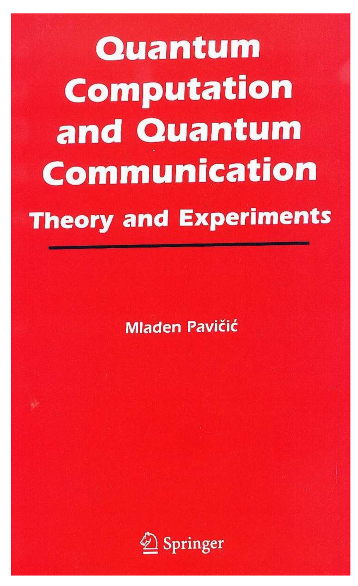


Figure 4. When the control state of a CNOT gate is in a superposed state the gate entangles the qubits.

The proposal is based on a reversible classical CNOT-gate setup put forward in $\Longrightarrow$



[1] M. Pavičić, Nondestructive Interaction-Free Atom-Photon Controlled-NOT Gate, *Physical Review A*, **75**, 032342 (2007).