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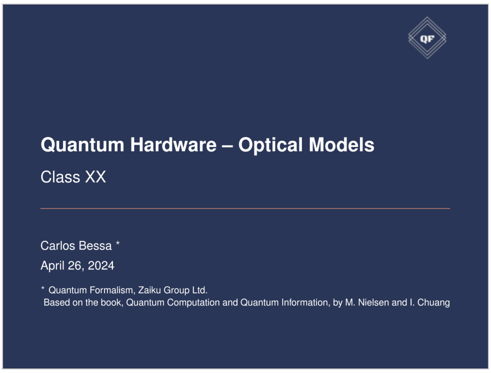
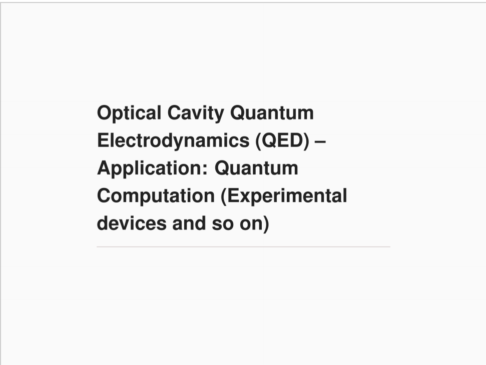
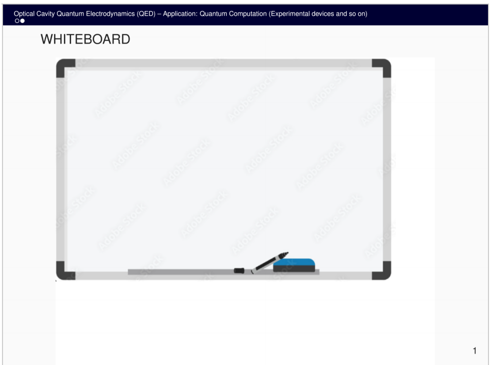
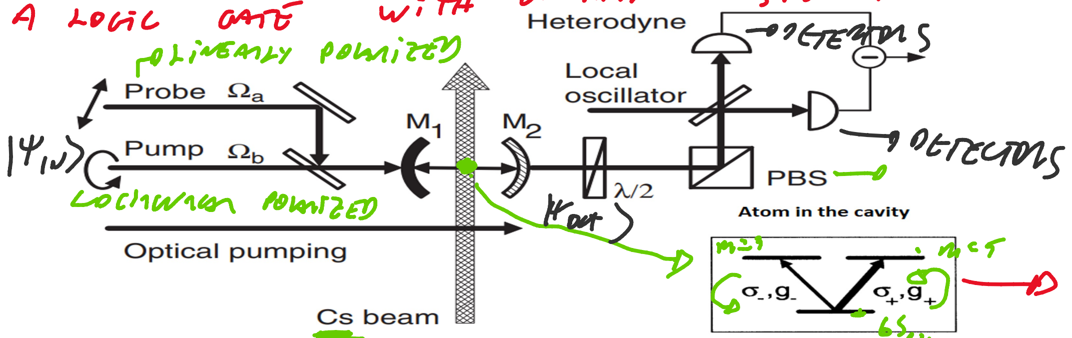






7.5.4 QUANTUM COMPUTATION

- FIGURE 7.6 ILLUSTRATES A CAVITY QED EXPERIMENT WHICH WAS PERFORMED TO DEMONSTRATE THE POTENTIAL FOR REALIZING A LOGIC GATE WITH UNITARY TRANSFORM



$|$FIELD a, FIELD b, ATOM$\rangle$

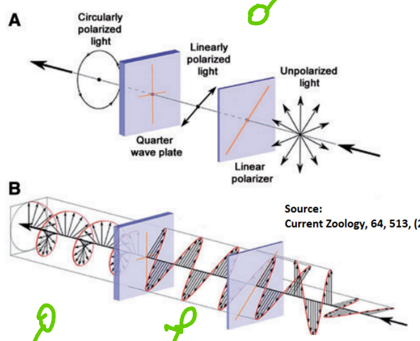
→ THREE-LEVEL ATOM

M_1, M_2 → MIRRORS

Figure 7.6. Schematic of an experimental apparatus used to demonstrate the possibility of using a single atom to provide cross phase modulation between single photons, as an elementary quantum logic gate. A linearly polarized weak probe beam of light Ω_a, and a stronger circularly polarized pump beam Ω_b are prepared and shone on an optical cavity with high reflectivity mirrors M_1 and M_2. Cesium atoms prepared in the electronic state $6S_{1/2}$, $F = 4$, $m = 4$ by optical pumping fall (the figure shows the atoms upside down) such that the average

Figure 7.6. Schematic of an experimental apparatus used to demonstrate the possibility of using a single atom to provide cross phase modulation between single photons, as an elementary quantum logic gate. A linearly polarized weak probe beam of light Ω_a, and a stronger circularly polarized pump beam Ω_b are prepared and shone on an optical cavity with high reflectivity mirrors M_1 and M_2. Cesium atoms prepared in the electronic state $6S_{1/2}, F = 4, m = 4$ by optical pumping fall (the figure shows the atoms upside down) such that the average number of atoms in the cavity is around one. The light traverses the cavity, interacting with the atom; σ_+ polarized light causes strong transitions to the $6P_{3/2}, F' = 5, m' = 5$ state, and the orthogonal σ_- polarized light causes weak transitions to the $6P_{3/2}, F' = 5, m' = 3$ state. The polarization of the output light is then measured, using a half wave plate, a polarizing beamsplitter (PBS), and a sensitive balanced heterodyne detector (which selectively detects light at a specific frequency, as determined by the local oscillator). Figure courtesy of Q. Turchette.

$M_1, M_2 \to$ mirrors



Source: Current Zoology, 64, 513, (2018)

circularly linearly

In the last lecture, the unitary gate is given by Eq. (7.87)

$$\underbrace{QPG}_{\text{CNOT}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\varphi_a} & 0 & 0 \\ 0 & 0 & e^{i\varphi_b} & 0 \\ 0 & 0 & 0 & e^{i(\varphi_a+\varphi_b+\Delta)} \end{pmatrix} \qquad (7.87)$$

- In the experiment mentioned in Fig. 7.6, two modes of light with weak coherent states are prepared

Input in the cavity:
- one linearly polarized light (the probe)
- one circularly polarized light (the pump)

- We represent this state as

$$|\psi_{in}\rangle = \underbrace{|\beta^+\rangle}_{\text{pump}} \left[\underbrace{\frac{|\alpha^+\rangle + |\alpha^-\rangle}{\sqrt{2}}}_{\text{probe}} \right] \qquad (7.88)$$

$\alpha^\pm$: probe { • linearly polarized light is an equal

PUMP PROBE

$\alpha^{\pm}$: PROBE
$\beta^{\pm}$: PUMP

• LINEARLY POLARIZED LIGHT IS AN EQUAL SUPERPOSITION OF THE TWO POSSIBLE CIRCULARLY POLARIZED STATES $(+,-)$

— WE SAW IN LECTURE 9 (NOTES 9, PAGE 6) THAT FOR A SINGLE MODE COHERENT STATE $(|\alpha\rangle)$

$$|\alpha\rangle = \left(e^{\alpha a^{\dagger} - \alpha^{*} a}\right)|0\rangle \; , \quad \begin{cases} a^{\dagger} \to \text{CREATION OPERATOR} \\ a \to \text{ANNIHILATION OPERATOR} \\ |0\rangle \to \text{FOCK STATE} \end{cases}$$

THE EXPERIMENT IS PERFORMED IN THE WEAK COHERENT STATES APPROXIMATION $(\alpha \ll 1)$

$$|\alpha\rangle = \left(1 + \alpha a^{\dagger} - \alpha^{*} a + \cdots\right)|0\rangle$$

$$|\alpha\rangle \simeq |0\rangle + \alpha|1\rangle$$

AND FOR $|\alpha^{\pm}\rangle$, $\Rightarrow$ $|\alpha^{\pm}\rangle \simeq |0^{\pm}\rangle + \alpha|1^{\pm}\rangle$

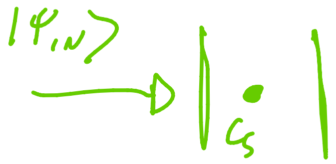
AND SIMILARLY FOR $|\beta\rangle$

$$|\beta^{+}\rangle \simeq |0^{+}\rangle + \beta|1^{+}\rangle$$

— IN THIS CASE WE HAVE

$$\to |\psi_{IN}\rangle \simeq \underbrace{\left[|0^{+}\rangle + \beta|1^{+}\rangle\right]}_{\text{PUMP}} \overbrace{\left[|0^{+}\rangle + \alpha|1^{+}\rangle + |0^{-}\rangle + \alpha|1^{-}\rangle\right]}^{\text{PROBE}} \qquad (7.89)$$

WHERE THE NORMALIZATIONS FACTORES WERE DESCONSIDERED



– THE PHOTONS PASS THROUGH THE OPTICAL CAVITY AND INTERACT WITH THE ATOM

– THE ATOM IS MODELED AS CAUSING A DIFFERENT PHASE SHIFT TO OCCUR TO STATES DEPENDING ON THE TOTAL NUMBER OF PHOTONS IN EACH POLARIZATION

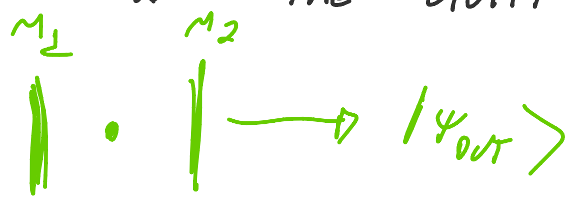
– SO, IT IS ASSUMED THAT A PHOTON IN THE $|1^+\rangle$ STATE EXPERIENCES A $e^{i\varphi_a}$ PHASE-SHIFT IF IT IS IN THE PROBE BEAM AND $e^{i\varphi_b}$ PHASE-SHIFT IF IT IS IN THE PUMP BEAM

$$\left.\begin{aligned}
|0^+0^+\rangle_{IN} &\rightarrow |0^+0^+\rangle_{OUT} \\
|0^+1^+\rangle_{IN} &\rightarrow e^{i\varphi_a}|0^+1^+\rangle_{OUT} \\
|1^+0^+\rangle_{IN} &\rightarrow e^{i\varphi_b}|1^+0^+\rangle_{OUT} \\
|1^+1^+\rangle_{IN} &\rightarrow e^{i(\varphi_a+\varphi_b+\Delta)}|1^+1^+\rangle_{OUT}
\end{aligned}\right\} \text{QPG}$$

THE OTHER STATES $(|0^-\rangle, |1^-\rangle)$ REMAIN UNCHANGED

– IN THE END WE WILL GET A CROSS-PHASE MODULATION SIMILAR TO THE ONE DESCRIBED IN SECTION 7.5.3

- THE OUTPUT FROM THE CAVITY IS



$$|\psi_{OUT}\rangle \approx |0^+\rangle\left[|0^+\rangle + \alpha e^{i\varphi_a}|1^+\rangle + |0^-\rangle + \alpha|1^-\rangle\right] + e^{i\varphi_b}\beta|1^+\rangle\left[|0^+\rangle + \alpha e^{i(\varphi_a+\Delta)}|1^+\rangle + |0^-\rangle + \alpha|1^-\rangle\right]$$

$$|\psi_{OUT}\rangle \simeq |0^+\rangle|\alpha, \varphi_a/2\rangle + e^{i\varphi_b}\beta|1^+\rangle|\alpha, (\varphi_a+\Delta)/2\rangle$$

WHERE,

- $|\alpha, \varphi_a/2\rangle = |0^+\rangle + \alpha e^{i\varphi_a}|1^+\rangle + |0^-\rangle + \alpha|1^-\rangle$
- $|\alpha, (\varphi_a+\Delta)/2\rangle = |0^+\rangle + \alpha e^{i(\varphi_a+\Delta)}|1^+\rangle + |0^-\rangle + \alpha|1^-\rangle$

EXPERIMENTAL RESULTS

- THE FIELD POLARIZATIONS ARE MEASURED BY THE DETECTOR

$\varphi_a \approx 17.5^\circ$, $\varphi_b \approx 12.5^\circ$, $\boxed{\Delta \approx 16^\circ}$

φ_a: 1 PHOTON

φ_b: 1 PHOTON

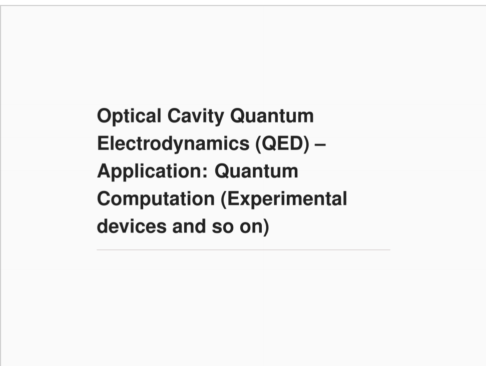
$1_a, 1_a \rightarrow$ IF LINEAR $\Rightarrow \varphi_a + \varphi_b \rightarrow e^{i(\varphi_a+\varphi_b)}$ AND $\Delta = 0$

- BECAUSE Δ IS A NON-TRIVIAL VALUE ($\neq 0$), THIS RESULT SUGGESTS THAT A UNIVERSAL TWO QUBIT LOGIC GATE (SEE LAST LECTURE) IS POSSIBLE USING SINGLE PHOTONS

SUGGESTS THAT A UNIVERSAL TWO QUBIT LOGIC GATE (SEE LAST LECTURE) IS POSSIBLE USING SINGLE PHOTONS AND A SINGLE ATOM IN A CAVITY AS A NON-LINEAR OPTICAL KERR MEDIUM TO INTERACT PHOTONS

→ Q. A. TURCHETTE, C. J. HOOD, ET AL..
SOURCE: PHYSICAL REVIEW LETTERS, 75, 4710, (1995)

Lecture25...



Optical cavity quantum electrodynamics

The experiment does demonstrate fundamental concepts required for quantum information processing. It certifies that nonlinear optical behavior such as the Kerr interaction really does occur at the single photon level, thus validating the essence of the Jaynes–Cummings model.

Ψ) Qubit representation: Location of a single photon between two modes, $|01\rangle$ and $|10\rangle$, or polarization.

Ψ) Unitary evolution: Arbitrary transforms are constructed from phase shifters (R_z rotations), beamsplitters (R_y rotations), and a cavity QED system, comprised of a Fabry–Perot cavity containing a few atoms, to which the optical field is coupled.

Ψ) Initial state preparation: Create single photon states (e.g. by attenuating laser light).

Ψ) Readout: Detect single photons (e.g. using a photomultiplier tube).

Ψ) Drawbacks: The incident photons are absorbed with non-trivial probability when traversing the cavity and atom, and thus the true quantum operation performed is not unitary; this problem would be aggravated if multiple gates were cascaded, which would be required, for example, to realize a CNOT-gate (which requires $\Delta = \pi$). In fact, reflection losses of the cavity arrangement used in this experiment would significantly impede cascading

Ψ) Drawbacks: The coupling of two photons is mediated by an atom, and thus it is desirable to increase the atom–field coupling. However, coupling the photon into and out of the cavity then becomes difficult, and limits cascadibility.