ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Termpaper

The Nobel Prize in Physics 2012

Author:
Fabian Thielemann

Supervisor:
Prof. Dr. Marcel Mudrich

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Some theoretical concepts of quantum optics are necessary to understand the ways in which Serge Haroche and David Wineland experimentaly observed fundamental quantum mechanical effects. This section aims to introduce the basic model of a fully quantum mechanical description of atom-light interaction, the Jaynes-Cummings model, and one of the most used results of it, namely Rabi oscillations.

2.1 Jaynes-Cummings Hamiltonian

Rabi cycles are a phenomenon that occurs when an atom interacts with light. Both, Serge Haroche and David Wineland, investigated and made use of the shifts in energylevels and relative phases of states that appear when a laser shines in on an atom. In order give a useful and complete description of Raby cycles, one has to take into account that the energy levels of the atom and of the photon field are quantized. The first "fully quantized" approach for the case of coherent light in a cavity and a two level system was given by Edwin Jaynes and Fred Cummings in 1963 [1]. To describe the system (following [2]) we introduce the total Hamiltonian, consisting of the Hamiltonian for the quantized photon field for a single mode, the Hamiltonian of the two level system consisting of a ground state $|g\rangle$ and an excited state $|e\rangle$ and the interaction Hamiltonian

$$\hat{H} = \hat{H}_{\text{field}} + \hat{H}_{\text{atom}} + \hat{H}_{\text{int}}, \tag{1}$$

where, neglecting the zero point energies of field and atom,

$$\hat{H}_{\text{field}} = \hbar\omega_{\text{f}}\, \hat{a}^\dagger \hat{a} \tag{2}$$

$$\hat{H}_{\text{atom}} = \frac{\hbar\omega_a}{2}\, \hat{\sigma_3} \tag{3}$$

$$\hat{H}_{\text{int}} = \hbar\omega_{\text{int}} \left(\hat{\sigma}_+ + \hat{\sigma}_-\right) \left(\hat{a} + \hat{a}^\dagger\right). \tag{4}$$

Here $\hat{a}^\dagger$ and $\hat{a}$ are the creation and annihilation operators that appear in the quantization of the electromagnetic field[1], the Pauli matrix $\hat{\sigma_3} = |e\rangle\langle e| - |g\rangle\langle g|$ acts as the inversion operator of the atom, and the associated Pauli matrices $\hat{\sigma}_+ = |e\rangle\langle g|$ and $\hat{\sigma}_- = |g\rangle\langle e|$ project any state $|g\rangle$ ($|e\rangle$) to $|e\rangle$ ($|g\rangle$) respectively and can thus be seen as atomic transition operators. It is now useful to look at the time evolution of the terms in the total Hamiltonian (1). To do so we switch to the interaction picture, using the Hamiltonian without interaction $\hat{H}_0 = \hat{H}_{\text{atom}} + \hat{H}_{\text{field}}$ to describe the time evolution of the operators. For the annihilation operator we have

$$\hat{a}(t) = e^{i\hat{H}_0 t/\hbar}\, \hat{a}(0)\, e^{-i\hat{H}_0 t/\hbar}$$

[1] To solve the free field equation of the elmg. field one usually uses the Fourier ansatz

$$A^\mu(x) = \int \mathrm{d}\tilde{k} \sum_{\lambda=0}^{3} \left[a_\lambda(\vec{k})\epsilon_\lambda^\mu(k)\mathrm{e}^{-ikx} + a_\lambda^\dagger(\vec{k})\epsilon_\lambda^\mu(k)^*\mathrm{e}^{+ikx}\right],$$

where λ goes over all possible polarizations. When demanding that A^μ and its conjugate field π^ν obey the canonical quantization relation, the resulting commutator relations for a_λ and $a_\lambda^\dagger$ allow the interpretation as creation and annihilation operators.

using the Baker-Campbell-Hausdorff formula, we obtain

$$= \hat{a}(0) + \frac{it}{\hbar}\left[\hat{H}_0, \hat{a}\right] + \frac{1}{2!}\left(\frac{it}{\hbar}\right)^2 \left[\hat{H}_0, \left[\hat{H}_0, \hat{a}\right]\right] + \dots$$

The first commutator is $\left[\hat{H}_0, \hat{a}\right] = -\hbar\omega_f \hat{a}$ as $\hat{a}$ commutes with $\hat{H}_{\text{atom}}$ and $\left[\hat{a}^\dagger, \hat{a}\right] = -1$. The nested commutators will thus only add higher orders of ω_f. The time evolution then becomes

$$\begin{aligned} &= \hat{a}(0)\left(1 - it\omega_f + (it\omega_f)^2 + \dots\right) \\ &= \hat{a}(0)e^{-i\omega_f t}.^2 \end{aligned} \tag{5}$$

Correspondingly we obtain for the other operators

$$\hat{a}^\dagger(t) = \hat{a}^\dagger(0)e^{i\omega_f t} \tag{6}$$

$$\hat{\sigma}_\pm(t) = \hat{\sigma}_\pm(0)e^{\pm i\omega_a t} \tag{7}$$

and therefore the full interaction Hamiltonian becomes

$$\begin{aligned} \hat{H}_{\text{int}}(t) = \hbar\omega_{\text{int}} \big(&\hat{\sigma}_+\hat{a}\, e^{i(\omega_a-\omega_f)t} + \hat{\sigma}_+\hat{a}^\dagger\, e^{i(\omega_a+\omega_f)t} \\ &+\hat{\sigma}_-\hat{a}\, e^{-i(\omega_a+\omega_f)t} + \hat{\sigma}_-\hat{a}^\dagger\, e^{-i(\omega_a-\omega_f)t}\big). \end{aligned} \tag{8}$$

Assuming that the photon frequency ω_f is close to the transition frequency of the atom ω_a, i.e. $|\omega_a - \omega_f| \ll \omega_a + \omega_f$, the rotating wave approximation can be applied. This means that all terms in $\hat{H}_{\text{int}}$ that oscillate with $\omega_a + \omega_f$ are neglected. Doing this and transforming back to the Schrödinger picture leaves us with the total Hamiltonian

$$\hat{H}_{\text{tot}} = \hbar\omega_f \hat{a}^\dagger\hat{a} + \frac{\hbar\omega_a}{2}\hat{\sigma}_3 + \hbar\omega_{\text{int}}\left(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger\right). \tag{9}$$

The last two terms can be seen as processes in which the atom aborbs or emmits one photon from the field while respectively changing its internal energy state.

2.2 Rabi Oscillations

Having found a Hamiltonian that describes the interaction of an atom with light, it is now interesting to investigate how this interaction influences the dynamics of the system. The original states of atom and fiel will no longer be eigenstates of the system and thus undergo a continuous oscillation, called Rabi oscillation. Bot, Serge Haroche and David Wineland have made experimental use of this effect in order to prepare and manipulate states. To describe the dynamics it is first useful to split the Hamiltonian in (9) into two parts, namely

$$\hat{H}_I = \hbar\omega_f \underbrace{\left(\hat{a}^\dagger\hat{a} + |e\rangle\langle e|\right)}_{\text{excitation number } \hat{N}_e} + \hbar\left(\frac{\omega_a}{2} - \omega_f\right)\underbrace{\left(|e\rangle\langle e| + |g\rangle\langle g|\right)}_{\text{e}^- \text{ number projector } \hat{P}_e} \tag{10}$$

$$\hat{H}_{II} = -\hbar\underbrace{\left(\omega_a - \omega_f\right)|g\rangle\langle g|}_{\equiv\Delta} + \hbar\omega_{\text{int}}\left(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger\right). \tag{11}$$

[2] By looking at the preceeding footnote and considering that kx is a scalar product of four-vectors but the integration over $\mathrm{d}\tilde{k}$ is only over the three spatial components, we see that the time evolution behaviour is already built-in in this ansatz.

The first part $\hat{H}_I$ commutes with $\hat{H}_{\text{tot}}$ thus it is conserved over time and any interesting dynamics of the system are described by the second part. Let us now consider a state

$$|\psi(t)\rangle = C_1(t)\,|e\rangle\,|n\rangle + C_2(t)\,|g\rangle\,|n+1\rangle \tag{12}$$

with initial conditions $C_1(0) = 1$ and $C_2(0) = 0$. The time evolution is described by the time dependend Schrödinger equation $i\hbar\frac{\mathrm{d}}{\mathrm{d}t}\,|\psi(t)\rangle = \hat{H}_{II}\,|\psi(t)\rangle$. In the resonant case ($\Delta = 0$) this can be exactly solved and yields

$$C_1(t) = \cos\left(\omega_{\text{int}}\sqrt{n+1}\,t\right) \tag{13}$$

$$C_2(t) = -i\sin\left(\omega_{\text{int}}\sqrt{n+1}\,t\right) \tag{14}$$

We see that the state of a two level system can be manipulated by sending in coherent light, a technique that is crucial for many quantum optics experiments. In this context a nomenclatur for pulses is established, describing to what extent the light interacts with the atom. A pulse of light is called "$r\pi$-pulse" ($r \in \mathbb{R}$) if it interacts with an atom such that

$$\omega_{\text{int}}\sqrt{n+1}\,t = \frac{r\pi}{2}. \tag{15}$$

A commonly used type of pulse is for example the $\pi/2$-pulse that takes e.g. a pure state $|e\rangle\,|n\rangle$ to a superposition state $\frac{1}{\sqrt{2}}\left(|e\rangle\,|n\rangle - i\,|g\rangle\,|n+1\rangle\right)$. In the basis spanned by $\{|e\rangle\,|n\rangle\,, |g\rangle\,|n+1\rangle\}$ a $\pi/2$-pulse can be represented in matrix form as

$$U(\pi/2) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix}. \tag{16}$$

The repeated action of a $\pi/2$-pulse on a two level system is shown graphically in Fig. 1. It should be noted that starting from $|e\rangle\,|n\rangle$ and performing a full rabi cycle will introduce a global phase of -1 to the system. However this phase is not of physical importance when the two level system is closed and only measurable in comparison to a reference system.[3]

2.3 Dressed States

When we want to describe the dynamics of a two level system also in the off-resonant case requires diagonalization of the Hamiltonian (9). The resulting eigenstates are called "dressed states", a wording that suggests that they are atom states "dressed in light" in contrast to the "bare" states of the atom without a light field. Using again the basis $\{|e\rangle\,|n\rangle\,, |g\rangle\,|n+1\rangle\}$ we can represent (9) as

$$\hat{H}_{\text{tot}} = \begin{pmatrix} n\omega_f + \frac{1}{2}\hbar\omega_a & \hbar\omega_{\text{int}}\sqrt{n+1} \\ \hbar\omega_{\text{int}}\sqrt{n+1} & (n+1)\omega_f - \frac{1}{2}\omega_a \end{pmatrix} \tag{17}$$

and diagonalize it. From this we obtain the eigenenergies

$$E_\pm = \hbar\omega_f\left(n + \frac{1}{2}\right) \pm \hbar\Omega_n(\Delta) \tag{18}$$

[3] $\langle e|\hat{O}|e\rangle = \langle e|(-1)\hat{O}(-1)|e\rangle$ for any observable $\hat{O}$.

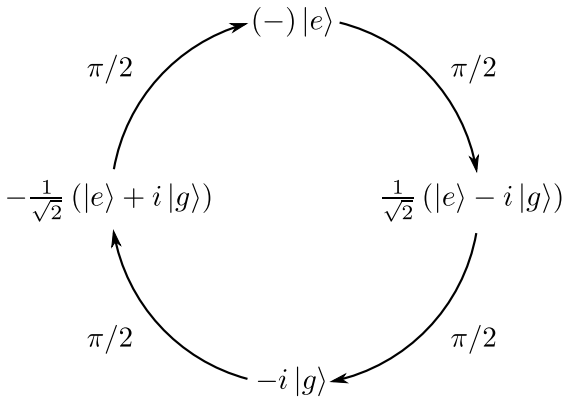


Fig. 1: Graphic representation of the action of a $\pi/2$-pulse on the state of a two level system. The photon number states (e.g. as in $|e\rangle\,|n\rangle$) are not shown explicitly. The $(-)$ in front of the excited state indicates the change of the total phase after one full cycle, which is of importance only if there is another state to which it should be compared in measurement.

with the off resonant Rabi frequency

$$\Omega_n(\Delta) = \sqrt{\Delta^2 + 4\omega_{\text{int}}^2(n+1)}. \tag{19}$$

The eigenenergies of the new eigenstates depend on the detuning of the light with respect to the atom transition. This shift in the energy levels is often referred to as the "AC-Stark-shift". The corresponding eigenstates in the given basis are

$$|n,+\rangle = \cos(\Phi_n/2)\,|e\rangle\,|n\rangle + \sin(\Phi_n/2)\,|g\rangle\,|n+1\rangle \tag{20}$$
$$|n,-\rangle = -\sin(\Phi_n/2)\,|e\rangle\,|n\rangle + \cos(\Phi_n/2)\,|g\rangle\,|n+1\rangle \tag{21}$$

where the angle Φ_n is given by

$$\Phi_n = \tan^{-1}\left(\frac{2\omega_{\text{int}}\sqrt{n+1}}{\Delta}\right) \tag{22}$$

which converges towards $\pi/2$ for $\Delta \to 0$. The dressed states are now useful for many applications in the field of quantum optics. Given a prepared state of a two level atom, one can determine the interaction of the atom with (not necessarily resonant) incident light by expressing the initial state in terms of the dressed states. As the dressed states are eigenstates of the total Hamiltonian their time evolution is trivial under application of the time evolution operator. In this way the dynamics can be calculated in the dressed states basis and afterwards (if needed) transformed back to the initial basis.

2.4 Far Off Resonance Case

The full Jaynes-Cummings Hamiltonian (1) without the rotating wave approximation can also be treated for the far-off resonant case $\Delta \gg \omega_a$. Interaction is in this case ruled by the effective Hamiltonian

$$\hat{H}_{\text{eff}} = \hbar\chi\left[\hat{\sigma}_+\hat{\sigma_-} + \hat{a}^\dagger\hat{a}\sigma_3\right], \tag{23}$$

where χ depends on the photon number n and the detuning Δ [2]. Under this Hamiltonian a state

$$|\Psi(0)\rangle = \frac{1}{\sqrt{2}} \left(|e\rangle |n\rangle + |g\rangle |n\rangle \right) \tag{24}$$

will evolve according to

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} \left(|e\rangle |n\rangle + e^{-i\chi(\Delta,n)t} |g\rangle |n\rangle \right), \tag{25}$$

a time evolution that Serge Haroche used to non-destructively detect single photons (see Sec. 3.3.3).

3 Serge Haroche

One half of the Nobel prize in physics 2012 was awarded to the french quantum physicist Serge Haroche. Serge Haroches main work concentrates on the field of cavity quantum eledtrodynamics (CQED), i.e. in his case the interaction of Rydberg atoms with single modes in a cavity. In this section we will follow some of the steps of his personal life and scientific carreer in order to understand how he made his way to the Nobel prize.

3.1 Early Life and Scientific Carreer

Serge Haroche was born 11 September 1944 in Casablanca, a major city at the moroccon atlantic coast, as the son of Albert and Valentine Haroche, both teachers at a local jewish school. At that time the southern part of Morocco was a French protectorate. However in 1956 Morocco gained independence and Haroches parents moved to Paris as they felt that they had themselves received and given their children a french education. Regarding his performance in school, Haroche seemed to have no problem settling in, as he was "immediately at the head of [his] class" [3] at his new school in Paris. After his "Baccalauréat"[4] he joined the for two years of continuous training and examination to eventually be admitted to one of the french elite universities. Being the best of his year in the national ranking, he was able to join "École normale supérieure"(ENS) in 1963 where he studied until 1967 and was taught, among others, by Alfred Kastler[5] and Claude Cohen-Tannoudji.[6] At the end of his studies he was "enthralled by the mysterious beauty of the quantum world" [3] and decided to continue his academic carreer in the field of quantum physics, more specifically quantum optics. He decided to write a PhD thesis with Cohen-Tannoudji as his supervisor on the dressed states formalism (see Sec. 2.3) and its implications on the description of optically pumped atoms. In the experiments he performed, he used spectral lamps as a light source but it became clear for him that he needed to learn how to apply lasers to his field of research.

Fig. 2: Serge Haroche in 2012. Source: *nobelprize.org*

After his PhD at ENS, Serge Haroche joined the group of Arthur Schawlow[7] at Stanford University from 1972 to 1973. Shortly before is arrival Theodor Hänsch[8] had joined the group as an associate professor, making him the fourth later Nobel laureate to work with Haroche. Schawlow gave a lab room and a pulsed dye laser to Haroche and told him that "it was up to [him] to find something interesting to do with it" [3]. As Haroche was already familiar with the dressed states formalism and saw the potential of the laser as a much more intense light source compared to classical lamps, he decided to probe quantum

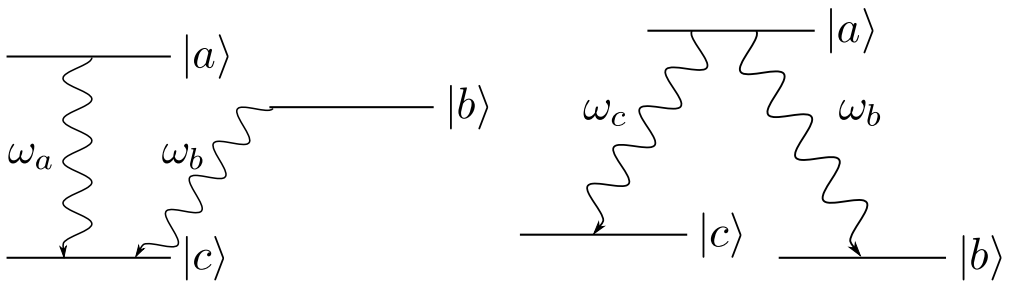
[4] The french correspondence to the german "Abitur".

[5] Nobel prize for physics in 1966 "for the development of optical methods for studying Hertzian resonances in atoms".

[6] Nobel prize for physics in 1997 "for the development of methods to cool and trap atoms with laser light".

[7] Nobel prize for physics in 1981 "for his contribution to the development of laser spectroscopy".

[8] Nobel prize for physics in 2005 "for his contribution to the development of laser-based precision spectroscopy".



(a) V-type atom (b) Λ-type atom

Fig. 3: Atom level schemes for which there should be quantum beat signals in the emmitted intensity in a semi-classical model. In QED only (a) shows quantum beats which is in accordance with experiment.

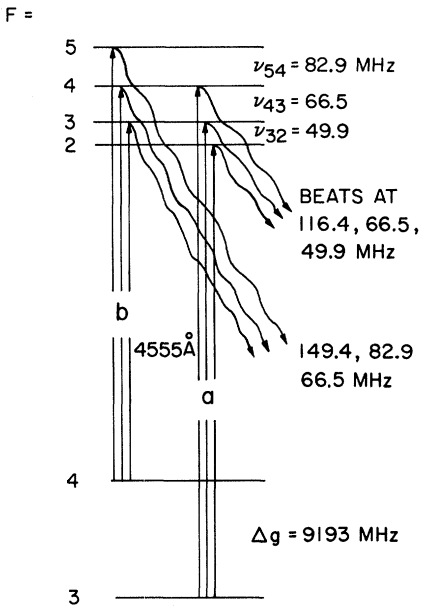
beat signals in cesium vapor [4]. The resulting paper will be discussed in Sec. 3.2. Still in Stanford Haroche sent a research proposal on the study of Rydberg atoms to one of the ENS directors and was immediately offered a position and start-up budget. His own research in the labs of ENS started in 1973 and has continued ever since with Rydberg atoms being a central pillar of many experiments.[9] At ENS Haroche had a position as "maître de recherche" that allowed him to fully focus on his research. However he was also keen to teach students, what drove him to take on a position as a full professor of physics at Université Paris VI. In the early 1980s Haroche started his research in the field of cavity quantum electrodynamics (CQED) on which all of his later explorations of fundamental quantum mechanical concepts are based. His research on CQED will be adressed with the discussion of some exemplary experiments in Sec. 3.3. At this time Haroche already had a good reputation as a scietist and was offered a position in Harvard in 1981 which he refused. When he was tempted again in 1984, this time by the University of Yale, he accepted and was appointed a professor while at the same time retaining his position in Paris. He kept the chair in Yale until 1993 and during this time was able to run succesful experiments on both sides of the atlantic [5, 9]. In 2001 Haroche was appointed professor of quantum physics at Collège de France [10]. The Collège de France is a prestigious institution at which scientists from different fields give lectures on their current research that are open to the public. In 2009 Haroche was awarded the gold medal of the Centre national de la récherche scientifique, one of the highest honors awarded to french scientists once a year.

3.2 Quantum Beats

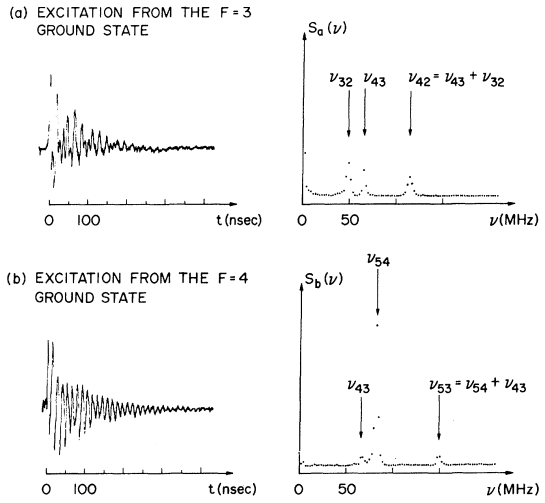
During his Postdoc in Stanford Haroche investigated the phenomenon of quantum beats that appear in the fluorescence intensity in some types of atoms when they are excited to a superposition of upper states and decay towards a common lower lying state [4]. Quantum beats where especially interesting as they could only be entirely described by quantum electrodynamics (QED), i.e. in a model in which not only the energy levels of the atom but also the states of the light field are quantized.

The two types of atoms that are interesting with regards to quantum beats are shown in Fig. 3. V-type atoms have two upper levels $|a\rangle$ and $|b\rangle$ that can decay to a common

[9] See for example [5–8]



(a) Level scheme of the Cesium hyperfine structure. Pulsed excitation from either of the lower levels (F=3,4) introduces the two possible sets of quantum beats *a* and *b* with beat frequencies indicated.



(b) Recorded intensities (left) and Fourier analysis (right) for the two different types of excitation. The frequency spectrum exhibits characteristic maxima in both cases.

Fig. 4: Hyperfine structure of cesium and experimentally measured fluorescence intensities, showing a quantum beat signal as predicted by QED.(Source: [4])

lower lying state $|c\rangle$ but transitions between them are dipole forbidden. Λ-type atoms consist of one upper level $|a\rangle$ that can decay to two different lower lying levels $|b\rangle$ and $|c\rangle$. Summarizing the QED calculations in [11], for V-type atoms one expects a modulation on top of the intensity signal of the form

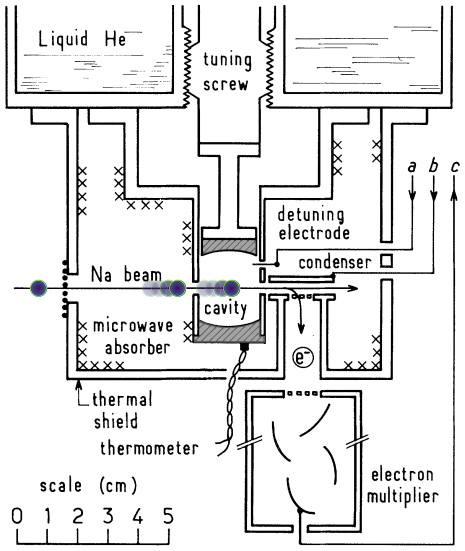
$$I_{tot}(t) = I_0 + I_{\text{beat}} \cos\{(\omega_a - \omega_b)\, t\} \tag{26}$$

whereas for Λ-type atoms, the beat term vanishes. This result is in disagreement with a semiclassical approach in which both types show a beat term. However only the QED results are consistent with performed experiments.

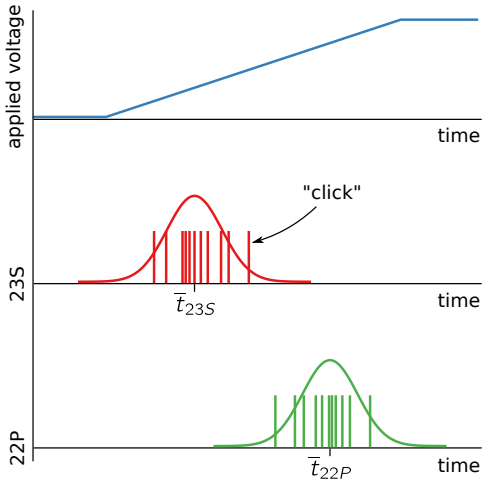
The system of interest for Serge Haroche was the Cesium hyperfine structure shown in Fig. 4a. The frequency bandwidth of the pulsed dye laser is smaller than the splitting of the two lower levels, but large enough to populate all possible upper states. This means that e.g. from the F=3 ground state, the F′=2,3,4 excited states can be populated according to the dipole selection rule. In this way two sets of upper states can be excited, namely *a* and *b* in Fig 4a. The expected beat frequencies are the three difference frequencies between the upper levels.

The experimental results are shown in Fig 4b. The fluorescence intensities on the left show a clear oscillating behaviour, with an exponentially decaying enveloppe caused by the characteristic damping of spontaneous emission. The plots on the right show the Fourier spectrum of the intensity signals. In each off them there are three characteristic peaks that correspond to the three beat frequencies indicated in Fig. 4a.

The resulting frequencies were in good agreement with other values that had been



(a) The superconducting cavity in the center can be tuned using a screw and is cooled by liquid helium. After crossing the cavity, the atoms states are detected in the ionization detector.



(b) The voltage applied to the condenser is increased in time. The different ionization energies of the 23S and the 22P states lead to different electron detection times in the electron multiplier.

Fig. 5: Experimental setup and ionization detection scheme used to observe cavity enhanced spontaneous emission. (Adapted from [5])

measured for the hyperfine structure of cesium. Although the uncertainties were higher than those of other state of the art spectroscopy methods there was a clear advantage of this method: once one is able to excite the upper states, there is no need to scan for resonance as the full intensity spectrum already exhibits the needed modulation. A very finely tunable laser is thus not necessary. Further, the precision of the method could be improved by increasing the sampling frequency and the total number of sample points taken.

3.3 Cavity Quantum Electrodynamics

After his first experiments in quantum optics, Serge Haroche soon turned towards his very own field of research: cavity quantum electrodynamics (CQED). CQED deals with the interaction of light that is confined in a cavity with atoms e.g. passing through it. The cavity can be used to engineer coherent photon number states $|n\rangle$ with n going down to 0 or 1. In this regime the quantum nature of light can be revealed. The following section will go through some of the experiments performed by Haroche that revealed or made use of the quantum behaviour of photons.

3.3.1 Enhanced spontaneous Emission

One of the first experiments of the ENS group of Haroche investigated the effect of enhanced spontaneous emission rates of an excited atom flying through a resonant cavity [5]. When an atom prepared in the upper of two levels, seperated by $\hbar\omega = \frac{h\lambda}{c}$, is brought into a cavity that is tuned to resonance with ω, the spontaneous emission rate will be increased

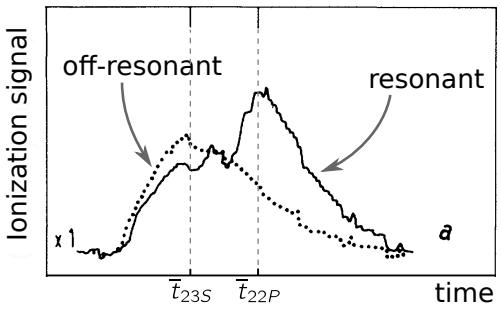


Fig. 6: Ionization signal of the atoms after crossing the cavity which is either off-resonant (dotted line) or resonant (solid line). An increased population of the 22P state is observed in the resonant case.

as

$$\Gamma_{\text{cav}} = \Gamma_0 \frac{3Q\lambda^3}{4\pi^2 V} \equiv \Gamma_0\, \eta_{\text{cav}}, \tag{27}$$

where Γ_0 is the natural decay rate, Q is the Q-value of the cavity and V its mode volume. Observations of this effect in the optical range (e.g. in Fabry-Perot interferometers) were impossible even for very high Q-values as the volume V is typically much larger than λ^3. Rydberg atoms played a key role in the detection, as their transitions are typically in the mm wavelength, an order of magnitude in which cavities can be manufactured.

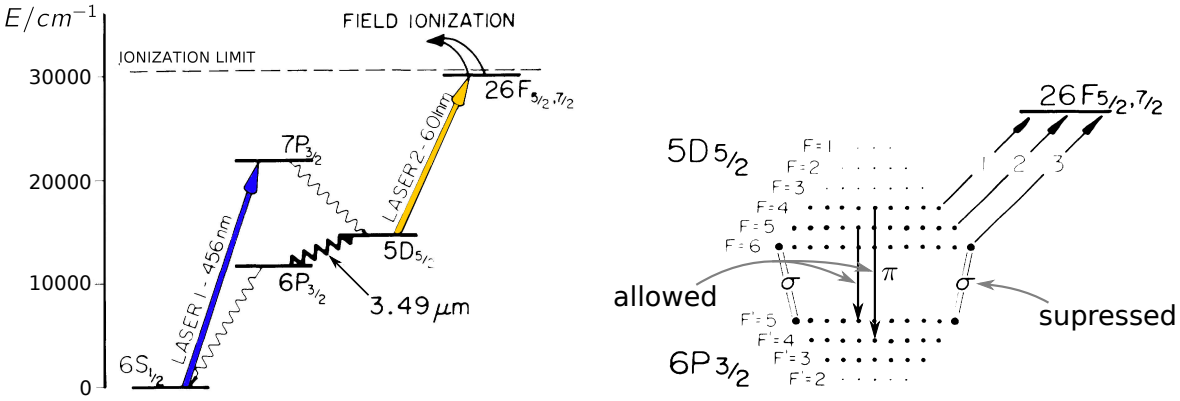
The experimental setup used by Haroche et.al. is shown in Fig 5a. The central part is the supeconducting niobium cavity cooled down to 5.7 K with an estimated Q-value of the order of 10^6 and an effective mode volume of $V = 70\,\text{mm}^3$, surrounded by an absorbant shielding to isolate it from background radiation. A micrometer screw allows tuning of the cavity's resonance frequency. To detect the increased spontaneous emission rate, sodium atoms are prepared in the 23S Rydberg state. The 23S $\rightarrow$ 22P transition has a wavelength of $\lambda = 0.88\,\text{mm}$ which makes observation of the effect possible for the given Q-value. The final state of the atoms, after having crossed the cavity, is determined by using a combination of a condenser and a time resolved electron detector. The detection scheme is depicted in Fig. 5b, showing the voltage applied to the condenser and two exemplary detection patterns in the electron multiplier as a function of time. One exploits the feature that the 23S state and the 22P state have different ionization energies. Ramping up the voltage with time will thus on average result in different ionization times corresponding to different electron detection times $\overline{t}_{23S}$ and $\overline{t}_{22P}$. When the cavity is tuned to resonance, the share of atoms in the 22P state should increase caused by an increase of the transition rate $\Gamma_{23S\rightarrow 22P}$.

This expectation exactly matches the experimental results shown in Fig. 6. One sees a clear shift of the peak in the ionization time histogram from $\overline{t}_{23S}$ to $\overline{t}_{22P}$ when the cavity is tuned from off-resonance to resonance. That means that tuning the cavity to resonance indeed increases the spontaneous emission rate as predicted by the CQED result (27).

Haroche and his group at ENS where the first to give experimental evidence of this CQED effect. But soon others followed. Namely the group of Haroche at Yale who were able to show that also a suppression of certain modes is possible using a similar experiment that will be described in the following section.

3.3.2 Supressed spontaneous Emission

Another interesting effect that a surrounding cavity can have on the energy states of an atom is the suppression of spontaneous emission. This effect was first experimentally realized by Haroche and his group in Yale in 1986 [9]. When the distance between the



(a) Level scheme of the used cesium atoms. Before entering the cavity, the atoms are prepared in the $5D_{5/2}$ state by excitation to $7P_{3/2}$ and spontaneous emission. The second laser drives the transition $5D_{5/2} \rightarrow 26F$.

(b) Hyperfine structure of the $5D_{5/2}$ and $6P_{3/2}$ levels. Due to the polarization dependend cut-off in the cavity, only π transitions are allowed. The F=6 substate of $5D_{5/2}$ can only decay via σ transitions.

Fig. 7: Relevant energy levels of cesium and their hyperfine structure. The different colors (blue and yellow) correspond to the two different lasers that are used.(Source: [9])

mirrors of the cavity d becomes smaller than half the wavelength λ of a certain transition in the atom, i.e.

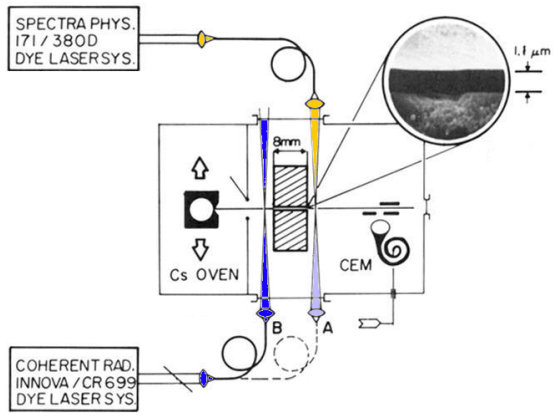
$$d < \frac{\lambda}{2}, \tag{28}$$

then all transitions of this wavelength that are σ polarized (i.e. parallel to the mirror surface) are supressed. A pictorial explanation would be the following: as the spontaneous emission rates depend on the vacuum fluctuations, but the boundary conditions imposed by the mirrors do not allow modes that fulfill (28), spontaneous emission for these modes is inhibited. Nonetheless, any π transition (polarized perpendicular to the mirrors) is still allowed and can even be enhanced. So to observe the anomalous survival of a state caused by a cavity, one needs to identify a state from which only σ decay is possible.[10]

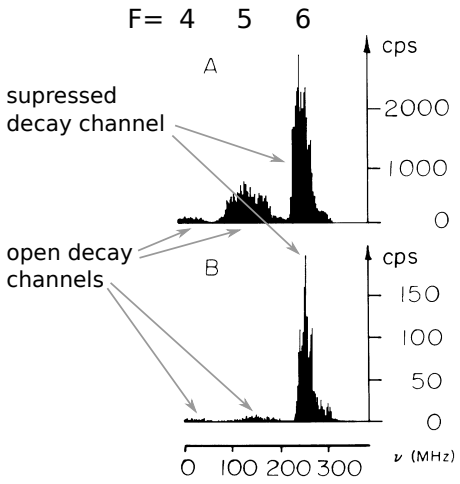
Haroche and his group chose to use cesium atoms and identified the $5D_{5/2}$ level to be suited for their purpose. As can be seen in the level scheme in Fig. 7a, the $5D_{5/2}$ level decays to the $6P_{3/2}$ level via emission of 3.49 µm radiation. Looking at the hyperfine structure of this transition shown in Fig. 7b we see that the F=6 substate of $5D_{5/2}$ can only decay via σ emission.

The setup that exploits this features of cesium is shown in Fig. 8a. A directed beam of cesium atoms is leaving an oven. First a pumping laser (blue) is used to prepare the

[10] In principle one could also calculate the change in the decay rate of a state depending on the share of π and σ transitions, but the survival of an else decaying state is easier to measure.



(a) The cavity used to cut off certain modes is 1 µm. Two lasers are used in cw mode, colored corresponding to the transitions shown in Fig. 7a. A condenser with constant voltage together with a channel electron multiplier (CEM) is used to detect the 26F state similar to the previous experiment.



(b) Resulting counting rates in the CEM as a function of the frequency of the detection laser (yellow). Shown for atoms not having crossed (A) and having crossed (B) the cavity. Only atoms in the F=6 substate survive the flight through the cavity.

Fig. 8: Setup and experimental results showing the supression of spontaneous emission of some of the transitions in the cesium hyperfine structure. (Adapted from [9])

atoms in the $5D_{5/2}$ state (see Fig. 7a). Next the atoms pass through the 1.1 µm wide cavity, made of gold coated fused silica blocks. A cavity of this size will supress any of the $5D_{5/2} \rightarrow 6P_{3/2}$ σ-transitions and thus supress any transition of the F=6 substate of $5D_{5/2}$ (see Fig. 7b). A 240 µT magnetic field perpendicular to the mirror surfaces will align the atoms along a common axis. After the cavity the atoms fly through the beam of the detection laser (yellow) that can be tuned around the $5D_{5/2} \rightarrow 26F$ transition hence selectively pumping atoms from the hyperfine levels of $5D_{5/2}$ to the Rydberg state 26F. Any atom in the 26F state will then be ionized in a condenser with a constant voltage of 1 kV, the ionization electron being detected in a channel electron multiplier.

In this way (again using the properties of Rydberg atoms) the relative populations of the several substates of $5D_{5/2}$ can be determined. The resulting counting rates of the CEM are shown in Fig. 8b. The upper histogram shows the counting rates depending on the resonant substate with the pumping laser placed directly before the detection laser. This corresponds to the relative populations resulting from the pumping process. The lower histogram shows the counting rates for the case in which the atoms interact with the pumping laser before entering the cavity and are pumped to the 26F by the detection laser after having traversed the cavity. Besides the fact that the counting rates are generally lower, due to a loss of atoms in the cavity, one sees that the peaks for the F=4 and F=5 substates of $5D_{5/2}$ almost vanish completely compared to the peak of the F=6 substate. This is experimental evidence that the decay of F=6 is strongly supressed by the surrounding cavity.

The preceeding experiments all show the behaviour of light as a quantum, yet the wave function of the photon was not observed in a direct manner. This would change with

Haroches experiments on quantum non demolition measurement of photons, which will be introduced in the next section.

3.3.3 Quantum Non Demolition Measurement of Photons

Many experiments (like the ones in the preceeding sections) show traces of the quantum nature of photons. However "in-vito", i.e. non destructive, measurement of the photons wavefunction was not performed until 2007,[11] when Haroche and his group at ENS introduced the first working experimental setup able to count an individual photon without destroying it. To implement the quantum non demolition (QND) measurement of photons, Haroche used many of the things he had learned about Rydberg atoms and their interaction with light in a cavity. A proof of concept paper about the technique had already been published in 1999 [7], but it took Haroche and his group another seven years to create a cavity with a Q-value so high that it could store photons with a typical lifetime of $\tau_\gamma = 0.1\,\mathrm{s}$ [12]. In this cavity thermal photons would survive long enough to interact with several hundreds of single atoms passing through the cavity [8].

An artists view of the setup is shown in Fig. 9a. Of course in reality the whole setup is vacuumized, shielded from the environment and cooled down to a few K similar to the setup shown in Fig. 5a. The cavity itself is cooled down to 0.8 K, a temperature at which the possibility of two thermal photons being excited is only 0.3%. The lifetime of resonant photons in the cavity was estimated to be 0.129(3) s by exciting a classical microwave in the cavity and measuring its ring-down time. A beam of single rubidium atoms is flying through the setup from left to right. In B they are pumped to a highly excited Rydberg state $|e\rangle \equiv |51\rangle$. R_1 and R_2 both apply $\pi/2$-pulses to the atom, tuned to resonance with the $|e\rangle \rightarrow |g\rangle \equiv |50\rangle$ transition. This setup is also called "Ramsey interferometer". The central part is the superconducting cavity, which is off resonant to the atoms and can or can not contain a thermal photon (the possibility of two thermal photons will be neglected). The atoms will obtain a phase shift due to the photon field in the cavity, that depends on the number of photons. At D the atoms will be detected either in the ground or in the excited state, following the principle of ionization detection introduced in Sec. 3.3.1.

To understand how exactly this setup measures the number of photons in the cavity (as long as it is 0 or 1) we will follow the wave function of the atom in a step by step manner. Initially the atoms are in the ground state and are excited to a Rydberg state in B giving

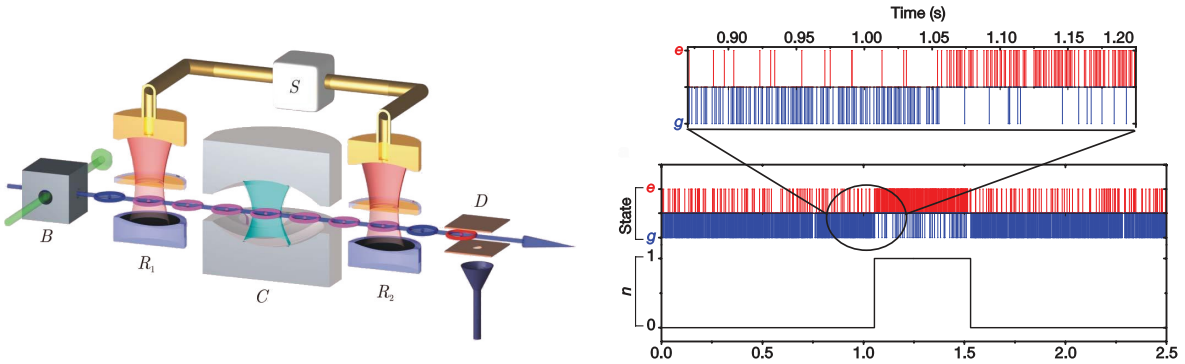
$$|\Psi_B\rangle = |e\rangle\,.$$

Next in R_1 a $\pi/2$-pulse will be applied to the atoms. According to Fig. 1 this will take the wave function to a superposition of excited and ground state

$$|\Psi_{R_1}\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle - i\,|g\rangle\right).$$

As the cavity is tuned to be far off resonance with the atoms, the time evolution of the wave function in the cavity will follow (25), introducing a phase shift in the superposition

[11] For example a photodiode detects photons by absorption of the photon and creatin of an electron-hole pair, that means the photons are destroyed in the detection process.



(a) Artist view of the setup used for QND measurement of photons. B prepares the atoms in a Rydberg state, R_1 and R_2 both apply a $\pi/2$-pulse to the atoms, D uses ionization detection similar to Fig. 5b, C is the superconducting cavity, cooled down to 0.8 K and detuned from the atom transition.

(b) Experimental results of the thermal photon detection. The upper trace shows whether the atom was detected in excited (red) or ground (blue) state. The lower trace shows the result of a majority vote, decreasing statistical error and fluctuations. A single photon was first detected at $t_0 \approx 1.05\,\mathrm{s}$ and observed by several hundreds of atoms during $\tau \approx 0.5\,\mathrm{s}$.

Fig. 9: Experimental setup and results of the first realization of quantum non demolition measurement of photons. (Source: [13])

state of the atoms after the cavity

$$|\Psi_{\mathrm{cav}}\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle - ie^{-i\Phi(\Delta,n)}\,|g\rangle\right).$$

To calculate the exact phase shift, one has to take into account the detuning of the cavity, the resonant Rabi frequency, the number of photons in the cavity, the transverse profile of the cavity mode and the time of flight of the atoms. But the key point is that some of these parameters, namely the detuning and the time of flight, can be adjusted such that

$$\Phi(\Delta, n) = \begin{cases} 0 & \text{for } n = 0 \\ \pi & \text{for } n = 1 \end{cases}$$

which results in the wave function

$$|\Psi_{\mathrm{cav}}\rangle = \begin{cases} \frac{1}{\sqrt{2}}\left(|e\rangle - i\,|g\rangle\right) & \text{for } n = 0 \\ \frac{1}{\sqrt{2}}\left(|e\rangle + i\,|g\rangle\right) & \text{for } n = 1 \end{cases}$$

At R_2 the atoms will receive another $\pi/2$-pulse which, again following Fig. 1, will transform the wave function to

$$|\Psi_{R_2}\rangle = \begin{cases} i\,|g\rangle & \text{for } n = 0 \\ -|e\rangle & \text{for } n = 1 \end{cases}$$

So by detecting in which Rydberg state the atoms are at D, one obtains information if there are 0 or 1 photons in the cavity. Note that the global phase of the wave function does not play a role in any physical measurement. The photon however was not absorbed by the atom, due to the far off detuning of the cavity and can be detected by the following atom as well until it changes its state again caused by external perturbation.

One resulting observed pattern is shown in Fig. 9b. Fluctuations that appear due to statistical uncertainties of the detection scheme are taken care of by plotting the majority vote, that means the classification of each event n is based on the results of n and the seven preceeding events. The shown trace thus shows a photon appearing due to fluctuations between thermal states and surviving in the cavity for approximately half a second, corresponding to a traveled distance of light of around 150 000 km folded in the cavity.

Haroche and his group found many other applications of this or similar setups, like engineering multi particle entanglement [14] and Schrödinger cat states [15] or observing the time evolution of photon number states in a cavity [16]. One could in principle dive arbitrarly deep into the principles of quantum optics just with the experiments of Serge Haroche at hand, but this would go far beyond the scope of this termpaper[12]. Summarizing his work from a current perspective, it shows an impressive continuity and coherence and definitely deserves[13] a Nobel prize as it tackled numerous fundamental topics of quantum mechanics and quantum electrodynamics.

[12] ...and the time available to the author.

[13] The author is aware of the fact that this judgement is not up to him, but anyways...

4 David Wineland

The second half of the Nobel prize in physics 2012 was awarded to the american quantum physicist David Wineland. David Winelands work was driven by the will to capture and take full control of single ions, leading for example to the development of Doppler cooling. In this section we will first address his early life and scientific carreer and then introduce important experimental methods he established.

4.1 Early life and scientific carreer

David Wineland was born the same year as Serge Haroche on February 24, 1944, in Wauwatosa, Wisconsin. His family moved to Sacramento, California in 1947 where he grew up and went to college. He describes his parents as marked by the great depression emphasizing "the importance of frugality and getting a good education" [17]. Having finished highschool in 1961, Wineland enrolled for a Math Major at the University of California. He soon realized that, working hard enough, he could make it too the top of his class. Still in his Junior year he changed his university and subject and took up a Physics Major at Berkeley. At the end of his undergraduate studies in physics he was not sure were to apply for a Master and PhD, but asking his classical mechanics teacher helped a lot: "he recommended Harvard, so I applied there". This said he started his studies at Harvard University in 1965 and soon joined the group of Norman Ramsey.[14]

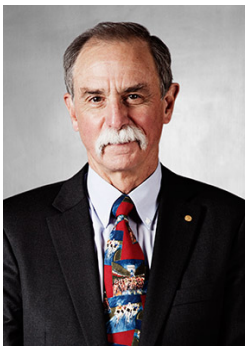


Fig. 10: David Wineland in 2012. Source: *nobelprize.org*

4.2 Doppler Cooling

4.3 Trapping Single Ions

4.4 Ion Quantum Jumps

4.5 Sideband Cooling

4.6 Quantum Logic Gate

[14] Nobel prize in physics 1989 "for the invention of the separated oscillatory fields method and its use in the hydrogen maser"

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