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Optical Shelving

The shelving phenomenon of quantum optics, originally observed by Dehmelt [1975], is analyzed in terms of the q-rules in Chap 9. The heuristic value of these rules is apparent because they not only describe the dark period during shelving, but they reveal the mechanism that enforces the suppression of fluorescence during that time.

The set-up

Given an atom with three energy levels a_0, a_1, and a_2, where a_0 is the ground state and a_1 and a_2 are excited states. The atom is exposed to two laser beams, one of excitation energy 0-1 and the other of excitation energy 0-2, where a_2 is a much longer lived state than a_1; so the 0-1 photons are stronger (i.e., more numerous) than the 0-2 photons. At time t_0 the atom begins in its ground state.

The atom will respond with the release of a strong photon. It then resets to ground and repeats the process, emitting another strong photon. This continues for a time called the *fluorescent period* during which a shower of many strong photons are rapidly released. Weak 0-2 photons do not appear during the fluorescent period. However, after a time the weak interaction does prevail, blocking the fluorescence and initiating a *dark period* that lasts for the half-life of a weak photon. Dehmelt originally explained this by saying that the atom occasionally jumps to the a_2 state where it is *shelved* until it decays again to ground. The atom is then *fully reset* to ground emitting a photon, and a fluorescent period begins again followed in time by another dark period [Pegg 1986, Porrati 1987].

It is not immediately clear how the weak interaction manages to cut off all fluorescent photons for so long a period of time. Why doesn't fluorescence always override the possibility of an occasional weak photon? This is the question raised by Shimony and others [Shimony 1993]. It is the purpose of this paper to answer this question using the q-rules of Chap. 9 that are claimed by the author to be auxiliary to Schrödinger's equation.

The Schrödinger solution to the shelving problem is given by T. Erber et al. [1989] and is of the form

$$a_0(t) = \cos[\Omega t]\ \exp[-\beta t] + A\ \exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \tag{11.1}$$

$$a_1(t) = i\ \sin[\Omega t]\ \exp[-\beta t] + A\ \exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \tag{11.2}$$

$$a_2(t) = \qquad - iB\ \exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \tag{11.3}$$

where Ω is the frequency and β is the decay constant of the strong interaction that produces fluorescence. The cosine in Eq. 11.1 and the sine in Eq. 11.2 identify this oscillation. There is no similar 'two-state' oscillation involving the 0-2 transition. Instead, there is a *three-state resonance* given by the exponential

$$\exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\}$$

This gives rise to the "dark period" where the slow decay constant λ insures a long half-life. When the sin/cos fluorescent components are extinguished, the remaining three-state resonance persists without (an immediate) radiation decay. Equations 11.1-11.3 do not include the reset radiation components so they do not preserve normalization over time. However, Shimony's question is still not answered. That is: What is the mechanism that suppresses fluorescence during the dark period? If the atom is not 'shelved' during this time as claimed by Dehmelt, then what enforces the fluorescent cut-off?

A q-rule analysis

The q-rules govern the behavior of quantum mechanical systems beyond the dynamic principle and are applied here to the shelving problem. A photon detector is not present because we assume that the shelving phenomena described above is objective – it does not depend on an external detector or observer making a so-called "null measurement". The initial state of the system at t_0 is given by

$$S(t_0) = \gamma_N \gamma'_M a_0 \tag{11.4}$$

where the radiation field contains N strong photons γ_N with a frequency between the levels 0 and 1, and M weak photons γ'_M of frequency between the levels 0 and 2.

After t_0 Eqs. 11.1-11.3 are represented by the following q-rule equations

$$\begin{array}{rl} & \Leftrightarrow \gamma_{N-1}\gamma'_M a_1 + \gamma_{N-1}\gamma'_M \underline{a}_0 \otimes \gamma \quad \text{fluorescence} \\ S(t \geq t_0) = \gamma_N \gamma'_M a_0 \ \Leftrightarrow & \\ & \Leftrightarrow \gamma_{N-1}\gamma'_M a_1 \Leftrightarrow \gamma_N \gamma'_{M-1} a_2 + \gamma_{N-1}\gamma'_M \underline{a}_0 \otimes \gamma + \gamma_N \gamma'_{M-1} \underline{a}_0 \otimes \gamma' \\ & \qquad \text{three-state resonance} \qquad\qquad \text{reset states} \end{array} \tag{11.5}$$

The initial component $\gamma_N\gamma'_M a_0$ in the middle row oscillates (double arrows) with both the top row making a two-state resonance and the bottom row making a three-state resonance. The components in these two rows are equal to zero at t_0. The part of $\gamma_N\gamma'_M a_0$ that oscillates with the three-state resonance has the same amplitude as the first component in the bottom row, so it too is zero at t_0. The laser induced two-state oscillation between a_0 and a_1 (top row) is given by the sin/cos components in Eqs. 11.1-11.3.

The last component in the top row of Eq. 11.5 represents the spontaneous emission (indicated by $\otimes$) of a fluorescent photon γ and a return of the atom to ground. It is a *ready component* as indicated by the underline of one of its states (in this case $\underline{a}_0$). Only a ready component is a candidate for state reduction according to the q-rules. With probability current flowing into it, a ready component is subject to a stochastic hit at each moment of time with a probability equal to the current times *dt*. All components except the chosen one are then reduced to zero. After being chosen in this way a ready component becomes a realized component and is no longer underlined.

If the ready component in the first row is stochastically chosen at some time t_{sc}, a wave collapse will yield a new solution given by

$$S(t = t_{sc} > t_0) = \gamma_{N-1}\gamma'_M a_0 \otimes \gamma \tag{11.6}$$

which is the same as Eq. 11.4 except that one of the γ photons has been removed from the laser beam and has become a radiated florescent photon. The first row in Eq. 11.5 is repeated many times during the fluorescent period.

The bottom row of Eq. 11.5 contains the radiationless three-state resonance. Probability current is 'stored' there until it is released through a spontaneous decay to one of the two reset states at the end of that row.

Although the initial state $\gamma_N\gamma'_M a_0$ contributes to both resonances, current flows much faster into the top row than it does into the bottom row. Also, the top row decays more rapidly. This means that the system is more likely to fluorescent decay before the three-state resonance has a chance to reset.

Sooner or later the initial state contribution to the two-state resonance will become depleted before it can decay, inasmuch as part of the initial state is tied up in the three-state resonance. At that point Eq. 11.5 becomes

$$\Leftrightarrow 0 + \gamma_{N-1}\gamma'_M\underline{a}_0\otimes\gamma \qquad \text{no fluorescence} \tag{11.7}$$

$$S(t \geq t_0) = \gamma_N\gamma'_M a_0 \Leftrightarrow \gamma_{N-1}\gamma'_M a_1 \Leftrightarrow \gamma_N\gamma'_{M-1} a_2 + \gamma_{N-1}\gamma'_M\underline{a}_0\otimes\gamma + \gamma_N\gamma'_{M-1}\underline{a}_0\otimes\gamma'$$

three-state resonance reset states

where the remaining ready component in the top row is dormant and serves no further purpose. At this point the bottom row in Eq. 11.7 will resonate at leisure, resulting in the dark period during which there is no fluorescence. That resonance decays with a long half-life λ and finally discharges through a spontaneous decay to one of the reset states at the end of that row. To the extent that a_1 in the three-state resonance is not zero it will decay to the first reset component; and to the extent that a_2 in that resonance is not zero it will decay to the second reset component. With the stochastic choice of one of these two ready components there will be a full reset that completes the dark period with the emission of a γ or a γ' photon.

This answers Shimony's question as to the mechanism that cuts off the fluorescent radiation during the long dark period. Fluorescent radiation is cut off because the initial component no longer feeds the two-state resonance. What remains of that component is engaged in the three-state resonance, and the only escape from that resonance to a full reset is through a long half-life spontaneous photon emission.

It is to be emphasized that the shelving phenomena described here is an objective property of the system and is not in any way dependent on the presence of an external detector or observer. The idea that the existence of a dark period depends ‘causally’ on the failure of a detector to see fluorescence makes no sense. A “null measurement” does not *produce* a dark period; rather, it is only a *consequence* of a dark period.