Shelving

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The shelving phenomenon of quantum optics, originally observed by Dehmelt, is analyzed in terms of the nRules that are given in another paper. 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.

Introduction

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 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. The weak 0-2 interaction is too slow to get a foothold before each of these resets take place, so weak 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 a time comparable to the half-life of a weak photon decay. 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 reset to ground emitting a weak photon, and a fluorescent period begins again, followed in time by another dark period [1-3].

It is understandable that the weak interaction does eventually produce a weak photon. However, 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 the fluorescence continue to appear, independent of an occasional weak photon? This is the question raised by Shimony [4]. It is the purpose of this paper to answer this question using the nRules that are auxiliary to Schrödinger's equation, and that are claimed by the author to describe the direction quantum mechanical processes [5].

The Schrödinger solution to the shelving problem is given in a paper by T. Erber et al. [6] and is of the form

$$a_0(t) = \cos[\Omega t]\exp[-\beta t] + A\exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \quad (1)$$

$$a_1(t) = i\sin[\Omega t]\exp[-\beta t] + A\exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \quad (2)$$

$$a_2(t) = \qquad - iB\exp[i\Omega t]\{\exp[-\beta t] - \exp[-\lambda t]\} \quad (3)$$

where Ω is the Rabi frequency and β is a rapid decay constant of the strong interaction. The cosine in Eq. 1 and the sine in Eq. 2 identify the 0-1 Rabi oscillation that produces fluorescence. There is no similar 'two-state' oscillation involving the 0-2 transition. Instead, there is a *three-state resonance* given by the exponential component

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

appearing in all three states. This correspond 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 radiation, hence the "darkness" of that decay. Equations 1-3 do not show the reset components, so they do not preserve their normalization over time – they all go to zero as time goes to infinity.

However, Shimony's question is still not answered. Equations 1-3 certainly do reveal the existence of a dark period uninterrupted by fluorescence; but the question is: How is fluorescence suppressed during the dark period? What is the mechanism that cuts it off when the atom is engaged in a three level resonance? If the atom is not 'shelved' during the dark time as claimed by Dehmelt, then what enforces the fluorescent cut-off?

An nRule Analysis

The nRules are four auxiliary rules that govern the behavior of quantum mechanical systems. They are listed in Ref. 5 together with examples that cover microscopic systems as well as macroscopic systems, with or without an observer. They are presumed to be universally applicable to any non-relativistic system. In the following, these rules are applied to the shelving problem. The system considered consists of a single atom and two laser beams. 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 of any kind.

The initial state of the system at t_0 is given by

$$\Phi(t_0) = \gamma_N \gamma'_M a_0 \tag{4}$$

where the time dependence of each state is not shown in order to simplify the notation. The radiation field contains N strong photons γ_N of the excitation frequency between the levels 0 and 1, and M weak photons γ'_M of excitation frequency between the levels 0 and 2. Normalizing the square modulus is of no importance with the nRules because the Born rule is not a governing principle. Probability is introduced into nRule equations through probability current alone, and this is automatically normalized at each moment of time. Equations 1 through 3 are represented for times after t_0 by

$$\begin{aligned} \Phi(t \geq t_0) = \gamma_N \gamma'_M a_0 \Leftrightarrow \gamma_{N-1} \gamma'_M a_1 + \gamma_{N-1} \gamma'_M \underline{a}_0 \otimes \gamma \quad & \text{fluorescence} \\ + \{\gamma_N \gamma'_M a_0 + \gamma_{N-1} \gamma'_M a_1 + \gamma_N \gamma'_{M-1} a_2\} \quad & \text{resonance} \\ + \gamma_{N-1} \gamma'_M \underline{a}_0 \otimes \gamma + \gamma_N \gamma'_{M-1} \underline{a}_0 \otimes \gamma' \quad & \text{resonance reset} \end{aligned} \tag{5}$$

All the components following the initial component $\gamma_N \gamma'_M a_0$ are zero at t_0 and increase in time. The arrow in the first row goes in both directions. It is the laser induced Rabi oscillation between a_0 and a_1, given by the sin/cos components in Eqs. 1-3. The first full row of Eq. 5 is the same form as Eq. 13 of Ref. 5.

The last component in the first row of Eq. 5 represents the spontaneous emission of a fluorescent photon γ and a return of the atom to ground. It is called 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 nRules. With positive probability current flowing into it, a ready component is subject to a stochastic hit at some moment of time with a probability equal to the current times dt. All components except the chosen one are then reduced to zero. That is, the wave collapses around the stochastically chosen ready component. After being chosen in this way a ready component is not subject to further stochastic choice, for it is no longer 'ready' component, and is no longer underlined.

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

$$\Phi(t = t_{sc} > t_0) = \gamma_{N-1}\gamma'_M a_0 \otimes \gamma \tag{6}$$

which is the same as Eq. 4 except that one of the γ photons has been removed from the laser beam and is emitted as a florescent photon. The first row in Eq. 6 is repeated many times to give the fluorescent period.

The second row of Eq. 5 (curly brackets) is the radiationless three-state resonance. Probability current is 'stored' there until it is released through a spontaneous decay in the third row. Current does not really flow into the curly brackets from the initial component. Rather, the first component in the curly brackets is a part of the initial component that is caught up in the three-state resonance. Current flow from there to the other curly bracket components is reversible, so none of the resonance components are ready components[1].

If the initial component $\gamma_N\gamma'_M a_0$ were to discharge exclusively to the first row, then it is certain that a fluorescent photon would be produced and the system would be reset. However, some small part of the initial component always gets caught up in the curly bracket resonance, so the initial component might become zero *before* a fluorescent emission. In that case Eq. 5 becomes

$$\begin{aligned} \Phi(t \geq t_0) = 0 \Leftrightarrow 0 + \gamma_{N-1}\gamma'_M \underline{a}_0 \otimes \gamma \quad & \text{fluorescence} \\ + \{\gamma_N\gamma'_M a_0 + \gamma_{N-1}\gamma'_M a_1 + \gamma_N\gamma'_{M-1} a_2\} \quad & \text{resonance} \\ + \gamma_{N-1}\gamma'_M \underline{a}_0 \otimes \gamma + \gamma_N\gamma'_{M-1} \underline{a}_0 \otimes \gamma' \quad & \text{resonance reset} \end{aligned} \tag{7}$$

Current cannot go from the second to the first row in this equation, so current flow into the ready component in the first row is not sustained. As a result, that component becomes a *phantom* as defined in Ref. 5. It can no longer be stochastically chosen because there is no longer a positive probability current flow into it. Therefore, Eq. 7 begins the dark period during which the release of a fluorescent photon is prohibited until there has been a reset by some other means. It is important to this argument that current cannot flow reversibly out of the three-state resonance. Otherwise

[1] The nRules require that a ready component is the result of an interaction that is irreversible and discontinuous in some variable. The components in the curly bracket of Eq. 5 are discontinuous among themselves, but they are not irreversible.

it would leak back into the initial component that would continue to feed the fluorescent ready state in the first row, thereby ending the dark period prematurely.

Since the second row has no ‘reversible’ means of releasing current, all it can do long-term (i.e., with half-life λ) is discharge through the irreversible spontaneous decay components in the third row. To the extent that the a_1 component in the resonance is non-zero, it will leak current irreversibly to the first component in the third row; and to the extent that the a_2 component in the resonance is non-zero, it will leak current irreversibly to the second component in the third row. With the stochastic choice of one of these ready components, there will be a 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. That mechanism is *the inability of the three-state resonance to interact reversibly* with the Rabi oscillators. The only escape for the resonance current is through a long half-life spontaneous and ‘irreversible’ photon emission.

One might ask why there exists a three-state resonance with these properties. Why isn’t the second row in Eq. 5 similar to the first, applied between the 0^{th} and the 2^{nd} components? That is a matter to be decided by the Schrödinger equation, not the nRules. If several competing processes are possible, or seem possible, then it is our claim that while each must conform to the requirements of the nRules, only Schrödinger’s equation can determine the relative cross section of each. The irreversibility of the curly brackets a whole is therefore a result of Schrödinger dynamics. Presumably, it results from a captive phasing that exists among the components of the three-state resonance.

It is well to be reminded at this point that normalization of the total square modulus is never an issue in the nRules, for normalization is achieved by normalizing the probability current at each moment of time. Also 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 detect fluorescence makes no sense. A “null measurement” does not produce the dark period. Rather, a null measurement is a consequence of a dark period.

References

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