Duration of information storage by means of the stimulated photon echo

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The time over which information can be stored by means of the stimulated photon echo should depend strongly on the total angular momentum of the ground state of the resonant atoms and on the polarizations of the exciting pulses.

The stimulated photon echo is formed by a sequence of three exciting pulses which are at resonance with a transition $b \rightarrow a$ of the atoms of the medium.[1] The first two pulses (the "writing pulses"), separated by a time interval τ_1, create nonequilibrium velocity distributions of the atoms in the upper and lower resonant levels. This deviation from equilibrium gives rise to a stimulated-photon-echo signal in the medium at a time τ_1 (the "reproduction time") after the passage of the third ("readout") pulse through the medium. The information storage time is thus determined by the time interval (τ_2) between the second and third exciting pulses, during which the deviation from the equilibrium velocity distribution of the atoms is retained in the medium. For gases, the time τ_2 is limited in any case by the transit times T_{tr} and by the scale times (T_a and T_b) for the thermalization of the velocity distributions of the atoms in resonant levels a and b, respectively, as a result of their collisions with each other or with atoms of buffer gases. Under the actual conditions in experiments on the stimulated photon echo, the time τ_2 is usually limited by some significantly shorter times: the relaxation times corresponding to spontaneous radiative transitions and elastic depolarizing collisions, i.e., collisions which do not change the velocities of the atoms but which do change their distribution in the Zeeman sublevels of the resonant levels. We will accordingly restrict the discussion below to only the last two of these relaxation processes.

In experiments on the stimulated photon echo, state a is usually the ground state, while state b can be any excited state which is coupled to the ground state by an optically allowed transition. In this letter we will assume that state a is the ground state, while state b can undergo a radiative decay only to state a. This is the situation, for example, in a study of the stimulated photon echo in ^{174}Yb vapor[2] or ^{23}Na vapor.[3]

The state of the atoms in level α ($\alpha = a,b$), with total angular momentum J_α, is characterized by the multipole moments of the density matrix of order κ ($0 \leqslant \kappa \leqslant 2J_\alpha$). The zeroth moment ($\kappa = 0$) describes the total population of the level. The relaxation of each multipole moment due to elastic depolarizing collisions occurs in a manner independent of the other moments and is characterized by a time $1/\Gamma_\alpha^{(\kappa)}$. We have $\Gamma_\alpha^{(0)} \equiv 0$, since elastic collisions do not change the level population. Under the influence of spontaneous radiative processes, all of the multipole moments of the upper level decay in an identical time $1/\gamma$ and are transferred to the lower level. The population is transferred completely, but the higher-order multipole moments ($\kappa > 0$) are not transferred completely, since part of the angular momentum is carried out of the system by photons. This circumstance has the consequence that after a time interval $1/\gamma$ all of the atoms are in the ground state, but the deviation from an equilibrium velocity distribution of these atoms is retained only in states with $\kappa \neq 0$. Only these states contribute to the stimulated photon echo. We should emphasize that since the transition $b \rightarrow a$ is optically allowed, the time $1/\gamma$ is usually short.

To support these arguments, we derive an expression for the electric field $\mathbf{E} \sim \mathbf{e}(\tau_2)$ of the stimulated photon echo at $\tau_2 > 1/\gamma$. Ignoring the small recoil effects during spontaneous emission, we have

$$e_x(\tau_2) = \frac{1}{3}(2b_0 + b_2)\cos(\psi_2 - \psi_1) + b_2\cos(\psi_2 + \psi_1), \tag{1}$$

$$e_y(\tau_2) = b_1\sin(\psi_2 - \psi_1) + b_2\sin(\psi_2 + \psi_1), \tag{2}$$

$$b_x = \exp\left(-\Gamma_a^{(\kappa)}\tau_2\right)\begin{Bmatrix}\kappa & 1 & 1\\ J_b & J_a & J_a\end{Bmatrix}\left[\begin{Bmatrix}\kappa & 1 & 1\\ J_b & J_a & J_a\end{Bmatrix} + (-1)^{J_a+J_b}\right.$$
$$\left.\cdot\,(2J_b+1)\frac{\gamma}{\gamma + \Gamma_b^{(\kappa)} - \Gamma_a^{(\kappa)}}\begin{Bmatrix}\kappa & 1 & 1\\ J_a & J_b & J_b\end{Bmatrix}\begin{Bmatrix}\kappa & J_a & J_a\\ 1 & J_b & J_b\end{Bmatrix}\right]. \tag{3}$$

Here ψ_1 and ψ_2 are the angles made with the X axis by the polarization vectors of the first and second exciting pulses; the X axis runs along the direction of the polarization vector of the third exciting pulse, while the Z axis runs along the pulse propagation direction. We wish to emphasize that expressions (1)–(3) hold for arbitrary angular momenta J_a and J_b in the approximation of small areas under the exciting pulses; in the case $J_a = 0$ or $J_a = 1/2$—the most common cases in practice—these expressions also hold for arbitrary areas under the exciting pulses.

It follows from (1)–(3) that all transitions $b \rightarrow a$ can be classified in one of three groups. The first group includes the transition with the value $J_a = 0 (J_b = 1)$. In this case the ground state a is characterized only by its population, and the time over which information is stored by means of the stimulated photon echo for this transition is determined by the short radiative lifetime of the upper level. This situation is typical of, for example, experiments on the stimulated photon echo in ytterbium vapor.[2] The second group includes transitions with the value $J_a = 1/2 (J_b = 1/2$ or $J_b = 3/2)$. The ground state in this case is characterized by both its population ($\kappa = 0$) and its orientation ($\kappa = 1$). Elastic depolarizing collisions in the case $J = 1/2$, however, do not increase the rate of the orientation decay[1]: $\Gamma_a^{(1)} \equiv 0$. We then find from (1)–(3), for the transition $J_b = 1/2 \rightarrow J_a = 1/2$, for example, on which the stimulated photon echo is formed in sodium vapor,[3]

$$e_x(\tau_2) = 0, \qquad e_y(\tau_2) = (2/27)\sin(\psi_2 - \psi_1). \tag{4}$$

It follows from (4) that the information storage time in this case depends on the polarizations of the exciting pulses. If the writing pulses are polarized in a common plane ($\psi_1 = \psi_2$), we have $\mathbf{e}(\tau_2) = 0$, and the information storage time is limited by the radiative lifetime of the upper level. If, on the other hand, the writing pulses are polarized in different planes, then $e_y(\tau_2)$ is not zero and is independent of τ_2 in the relaxation model which we are using here. This result means that the time over which information is stored by means of the stimulated photon echo is limited in this case only by the times T_{tr} and T_a, which are long in comparison with $1/\gamma$. Expression (4) thus explains the experimental results in Ref. 3, where the time over which information was stored by means of the stimulated photon echo was considerably longer than the radiative lifetime of the upper level.

The third and final group of transitions includes all with $J_a > 1/2$. In this case, the ground state is characterized by many multipole moments, which decay under the influence of elastic depolarizing collisions. The time over which information on these transitions is stored depends on the relation between the radiative relaxation rate and the rate of relaxation due to elastic depolarizing collisions. If the gas pressure is high enough to satisfy $\Gamma_{a,b}^{(\kappa)} > \gamma$, the information storage time will be determined by the time $1/\gamma$, and the stimulated photon echo will be polarized along the polarization vector of the third exciting pulse. If the gas density is instead low, and the relation $\Gamma_{a,b}^{(\kappa)} < \gamma$ holds, then we find from (1)–(3) that the information storage time is determined by the maximum relaxation time $1/\Gamma_a^{(\kappa)} (\kappa > 0)$ of the multipole moments of the ground state.

In summary, we have shown that by choosing the resonant atoms of the medium and the polarizations of the exciting pulses appropriately one can extend the time over which information is stored by means of the stimulated photon echo in a gas to a value substantially longer than $1/\gamma$.

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