Spin manipulation by absorption-free optical pumping

M. Kitano,* K. Yamane, and T. Ikushima
Department of Electronic Science and Engineering, Kyoto University, Kyoto 606-8501, Japan

(Received 1 July 1998)

We present an optical pumping scheme by which atomic spin motion can be controlled without photon absorption in the fast pumping limit. The phenomenon can be understood in terms of the quantum Zeno effect and the interaction-free measurement in a spin-photon system. [S1050-2947(99)01005-7]

PACS number(s): 32.80.Bx, 03.65.Bz, 42.50.−p

I. INTRODUCTION

Optical pumping [1] is a very useful tool and is widely used in the fields of atomic and optical physics. Especially, it has played a crucial role in the recent development of laser cooling and trapping of neutral atoms. It can be used for state preparation as well as for monitoring atomic states. Optical pumping, by which the atomic population is transferred from one state to another via excited states, necessarily accompanies optical absorption and subsequent reemission. In this paper, we present an optical pumping scheme which is operative even though no light absorption (and of course no reemission) is associated.

Let us consider an atom with a $J=\frac{1}{2}$ ground state and a $J'=\frac{1}{2}$ excited state illuminated by σ_+ circularly polarized light. Because of the angular momentum conservation, only atoms in the $m_J=-\frac{1}{2}$ sublevel in the ground state can absorb the photon and go to the excited state. Atoms in the excited state fall back either to the $m_J=+\frac{1}{2}$ sublevel or to the $-\frac{1}{2}$ sublevel. Repeating this process, all atoms are eventually pumped to the $m_J=+\frac{1}{2}$ sublevel. Once all atoms have been completely pumped, the atomic vapor becomes transparent because atoms in the $m_J=+\frac{1}{2}$ sublevel do not absorb σ_+ light.

When a magnetic field perpendicular to the pumping direction is applied, the spins start to precess about it, or the transition from the $m_J=+\frac{1}{2}$ sublevel to the $-\frac{1}{2}$ sublevel takes place. But if the pumping light is strong enough, the atomic vapor remains almost completely polarized. At first sight one might consider that the polarization is maintained simply because the flipped atoms are optically pumped back to the $m_J=+\frac{1}{2}$ sublevel. Under certain conditions, however, the flipping itself is suppressed owing to the quantum Zeno effect [2–5]. By sending σ_+-polarized light, which does not couple to the $m_J=+\frac{1}{2}$ sublevel, and verifying no absorption, we can infer that the atom is in the $m_J=+\frac{1}{2}$ sublevel. This is the so-called negative-result or interaction-free measurement. Thus performed continuous measurement prohibits the transition induced by the magnetic field via the quantum Zeno effect. The pumping light, though not absorbed, has a crucial effect on the spin dynamics.

If we view this situation from the rotating reference frame in which the magnetic field is canceled by the rotation-induced effective field, the pumping direction rotates and the spin follows it. This corresponds to the *inverse* quantum Zeno effect [6–8]. The spin is redirected by the pumping light but no light absorption is associated. With this absorption-free optical pumping, we can freeze the spin motion against magnetic fields and also control the spin direction arbitrarily.

In the analysis of the quantum Zeno effect, what is interesting is the probability that the atom remains in the initial state. The probability asymptotically approaches unity as the frequency or the strength of measurement increases. In the present context, however, we are rather interested in the numbers of photons absorbed to hold the atom in the initial state. In Sec. II, using a simplified model, we will show that the (absolute) photon number asymptotically goes to zero as we increase the pumping light intensity. In Sec. III, we introduce a more realistic and experimentally feasible model to demonstrate the absorption-free optical pumping. It turns out that the existence of intrinsic spin relaxation tends to mask the absorption-free feature and complicates the asymptotic behavior of the consumed photon number.

In Sec. IV, in addition to the present one, we introduce two pumping schemes, both of which induce the quantum Zeno effect, and make a comparison. One scheme, which does accompany photon absorption, corresponds to the experiment done by Itano *et al.* to demonstrate the quantum Zeno effect. The other scheme, which is absorption-free, is closely related to the interaction-free measurement [9] and also to the null measurement [10].

II. MODEL

If we neglect the population of the excited state, the atom system can be described by a 2×2 density matrix ρ_g, reduced to the ground state. We can define a normalized spin (or magnetic moment) vector $\boldsymbol{m}$ as $\rho_g=\frac{1}{2}(1+\boldsymbol{m}\cdot\boldsymbol{\sigma})$, where $\boldsymbol{\sigma}$ represents Pauli's matrices; $\boldsymbol{m}=\boldsymbol{0}$ corresponds to the unpolarized state and $\boldsymbol{m}=\boldsymbol{e}_z$ to the completely polarized state. We use the unit coordinate vectors $\boldsymbol{e}_x, \boldsymbol{e}_y, \boldsymbol{e}_z$. If we apply the magnetic field $\boldsymbol{B}_0=B_0\boldsymbol{e}_y$, the initial spin $\boldsymbol{m}=\boldsymbol{e}_z$ starts to precess around $\boldsymbol{B}_0$ at the angular frequency $\Omega=\gamma_g B_0=\pi/T$, where γ_g is the gyromagnetic ratio.

We apply circularly polarized optical pulses propagating in the z direction. It is supposed that each pulse is intense enough to completely polarize the spin toward the z direction almost instantaneously.

The (average) number of photons absorbed for the complete pumping is

*Electronic address: kitano@kuee.kyoto-u.ac.jp

$$n_p(\theta)=\frac{1}{2}(1-\cos\theta)\,\eta^{-1}, \tag{1}$$

where $\cos\theta=\boldsymbol{e}_z\cdot\boldsymbol{m}$ and η is the pumping efficiency, which depends on the atomic level structure and the collisional mixing in the excited state. For $\boldsymbol{m}=-\boldsymbol{e}_z$, η^{-1} photons are required to flip it back to $\boldsymbol{e}_z$, while for $\boldsymbol{m}=\boldsymbol{e}_z$ no photons are absorbed.

Now we send optical pulses at $t=kT/N(k=1,2,\ldots,N)$. Without these N pulses, the initial spin $\boldsymbol{m}(0)=\boldsymbol{e}_z$ would evolve to $\boldsymbol{m}(T)=-\boldsymbol{e}_z$. Each optical pulse flips the spin back to $\boldsymbol{e}_z$ and the tilt angle θ never exceeds π/N. Thus the optical pulses suppress the evolution. With regard to the spin motion, everything appears quite normal but careful analysis uncovers a peculiar feature inherent in the quantum Zeno effect.

Let us estimate the total number of photons absorbed. For each pulse, $n_p(\pi/N)$ photons are absorbed and therefore the total number n_t is given by

$$n_t=Nn_p(\pi/N)=\frac{N}{2\eta}\left(1-\cos\frac{\pi}{N}\right)\sim\frac{\pi^2}{4\eta}\frac{1}{N}\quad(N\gg1). \tag{2}$$

In the limit of $N\rightarrow\infty$, n_t asymptotically tends to zero. It is surprising that almost no photons are absorbed (or reemitted) to freeze the spin motion if we send enough optical pulses. In practice, however, N is limited due to the finite pumping time.

Now let us look at the above situation from a reference frame rotating at Ω around the y axis. The magnetic field $\boldsymbol{B}_0$ is canceled by the effective field $-\gamma_g^{-1}\Omega\boldsymbol{e}_y$. Without the optical pulses the spin stays still. In this frame the pumping direction $\boldsymbol{u}_k$ changes one after another,

$$\boldsymbol{u}_k=\sin\frac{k\pi}{N}\boldsymbol{e}'_x+\cos\frac{k\pi}{N}\boldsymbol{e}'_z, \tag{3}$$

where the prime designates the moving frame. Accordingly the spin is guided from $\boldsymbol{e}'_z$ to $-\boldsymbol{e}'_z$. Thus the spin is flipped over without photon absorption. This is a realization of the *inverse* quantum Zeno effect.

It should be stressed that the above situation can physically be realized simply by rotating the apparatus with no magnetic field. (In this case, the apparatus is composed of the pumping beam alone.) In terms of the spins associated with the ground-state Zeeman sublevels, the spatial rotation is completely equivalent to the magnetic field. This is not true for the fictitious spin associated with a general two-level system. This is the reason why the special (rf and optical) pulse sequences are used in the proposed scheme for the inverse Zeno effect [7]. Therefore, the current system would be a convenient arena for the demonstration of the inverse Zeno effect.

III. CONTINUOUS PUMPING

Let us consider a more realistic and experimentally feasible model where the spins are continuously pumped. The spin evolution can be described by the Bloch equation:

$$\frac{d\boldsymbol{m}}{dt}=\gamma_g\boldsymbol{m}\times\boldsymbol{B}_0-\Gamma\boldsymbol{m}-P(\boldsymbol{m}-\boldsymbol{e}_z). \tag{4}$$

To be realistic, an isotropic spin relaxation in the ground state is introduced and its rate is represented by Γ. The optical pumping rate P is written as the product of the efficiency η, the absorption cross section σ, and the incoming photon flux ϕ, i.e., $P=\eta\sigma\phi$. The steady-state solution to Eq. (4) is

$$\boldsymbol{m}=-\frac{P\Omega}{(P+\Gamma)^2+\Omega^2}\boldsymbol{e}_x+\frac{P(P+\Gamma)}{(P+\Gamma)^2+\Omega^2}\boldsymbol{e}_z. \tag{5}$$

If we measure m_z, by monitoring the transmitted light, as a function of Ω, we have a well-known (power-broadened) Hanle effect signal of the ground state.

In the fast-pumping limit ($P\gg\Gamma,|\Omega|$), we see that the spin precession is frozen; $\boldsymbol{m}\sim\boldsymbol{e}_z-O(\Omega/P)\boldsymbol{e}_x$.

We estimate the number of absorbed photons n_t per half-precession period $T=\pi/\Omega$. The normalization with respect to the precession period is crucial because we are interested in the photons consumed to suppress the precession. With Eq. (5), we have

$$n_t=\frac{\pi}{\Omega}\sigma(1-m_z)\phi=\frac{\pi}{\eta}\frac{P}{\Omega}\frac{\Gamma(P+\Gamma)+\Omega^2}{(P+\Gamma)^2+\Omega^2}. \tag{6}$$

Hereafter to simplify the expressions we use $\nu_t=(\eta/\pi)n_t$ instead of n_t.

For $P\gg\Gamma$, ν_t can be split into two terms,

$$\nu_t\simeq\nu_\Gamma+\nu_Z=\frac{\Gamma}{\Omega}\frac{P^2}{P^2+\Omega^2}+\frac{P\Omega}{P^2+\Omega^2}. \tag{7}$$

The term ν_Γ, which is proportional to Γ, corresponds to the number of photons consumed to compensate the intrinsic spin relaxation. It approaches the constant value Γ/Ω as P is increased.

The term ν_Z accounts for the numbers of photons used to suppress the spin precession through the quantum Zeno effect. It asymptotically tends to zero as P increases.

In order to see the general asymptotic behavior represented by Eq. (6), ν_t is plotted as a function of $p=P/\Gamma$ and $\omega=|\Omega|/\Gamma$, in Fig. 1. This normalization is convenient because experimentally the optical power P and the magnetic field Ω can be varied easily compared with the spin relaxation rate Γ. The asymptotic behavior of ν_t is classified as follows:

$$\nu_t\sim\begin{cases} p/\omega & (\text{I:}\quad p<\omega),\\ \omega/p+1/\omega & (\text{II:}\quad \omega<p<\omega^2),\\ 1/\omega & (\text{III:}\quad \omega^2<p),\end{cases} \tag{8}$$

where $p\gg1,\omega\gg1$ are assumed. In region I, ν_t is proportional to the incoming flux p, namely, the photons are efficiently absorbed because the spins are rapidly rotated by the magnetic field. In region II, when p is increased, ν_t decreases owing to the Zeno effect down to $\nu_\Gamma\sim1/\omega$, the residual photon consumption due to the relaxation. In region III, we only have $\nu_\Gamma\sim1/\omega$.

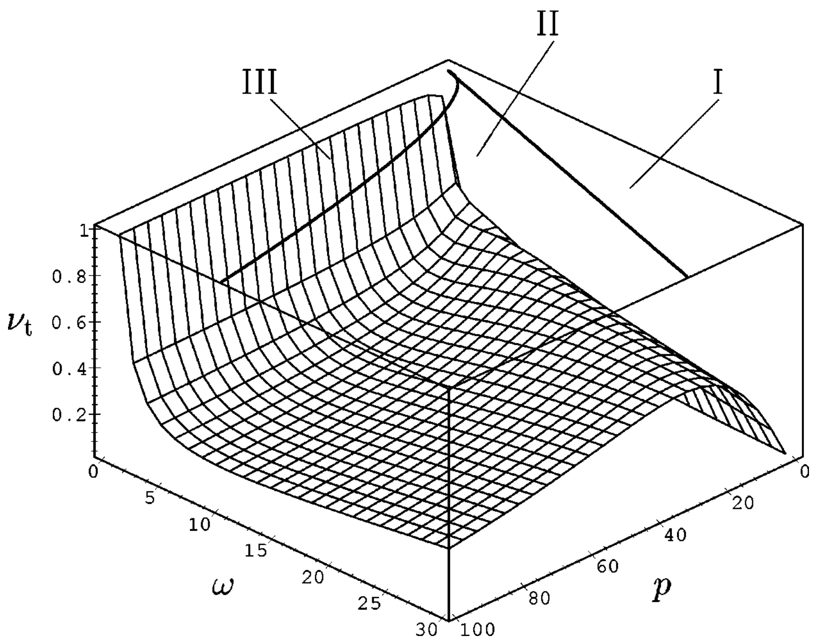

FIG. 1. Three-dimensional plot of normalized photon number ν_t as a function of p and ω. The (p,ω) plane is divided into three regions I, II, and III, according to the asymptotic behavior of ν_t.

If we increase p keeping ω fixed, we can observe the quantum Zeno effect in region II but eventually go into region III, where we have residual absorption. In order to reduce the absorption toward 0, ω must be increased like $\sqrt{p}$. In this case, the absorption reduces as $\nu_t \sim 1/\sqrt{p}$, being slower than $1/p$.

IV. DISCUSSION

In order to discuss our pumping scheme in a more general context, we consider level configurations shown in Figs. 2(a)–2(c). In all cases, only level 1 is initially populated and level 1 and 2 are coherently coupled by an external perturbation Ω. (In our case the Zeeman sublevels are coupled by the horizontal static magnetic field.) The coherent transition to level 2 is suppressed by (repetitive or continuous) optical excitation P to level 3.

Case (a). Level 1 is optically pumped to level 3 and all of the population decays back to level 1. In the fast pumping limit, the transition from levels 1 to 2 is inhibited. The pumping photons are continuously absorbed and reemitted. This corresponds to the level scheme used by Itano *et al.* [3] for demonstration of the quantum Zeno effect. In their case, levels 1 and 2 are not degenerate and the coherent transition is induced by microwaves. The detailed analyses are given in [4,5].

Case (b). Level 2 is pumped to level 3 and all of the population decays back to level 2. In this case, even though the empty level (level 2) is pumped, the coherent transition from level 1 to level 2 is inhibited. Unlike case (a), no photons are absorbed or remitted. The suppression of transition for this case was verified also by Itano *et al.* [3] but there seems no explicit reference to the associated photon absorption. This situation has a close connection to the so-called interaction-free measurement [9] and also to the null measurement [10].

Case (c). Level 2 is optically pumped to level 3 and some fraction $\eta(\neq 0)$ of the population decays to level 1 and $1-\eta$ to level 2. This corresponds to our present situation and reduces to case (b) when $\eta=0$. As in cases (a) and (b), the transition is suppressed but it is difficult to distinguish whether it is due to the quantum Zeno effect or just a population transfer by the optical pumping. We have seen that the former is the case in the fast pumping limit. It can be confirmed by monitoring photon absorption.

Cases (a) and (b) present a striking contrast; in the former case the population is transfered between levels 1 and 3, photons being scattered, while in the latter case neither population transfer nor photon scattering takes place. In either case, despite the difference in the pumping scheme, the time evolution of ρ_{12}, the coherence between levels 1 and 2, due to the optical pumping can be written as

$$\left.\frac{d\rho_{12}}{dt}\right|_{\text{pump}} = -P\rho_{12}. \tag{9}$$

This relaxation plays a crucial role in causing the quantum Zeno effect. Case (c) is rather similar to case (b), but the additional repumping term, represented by

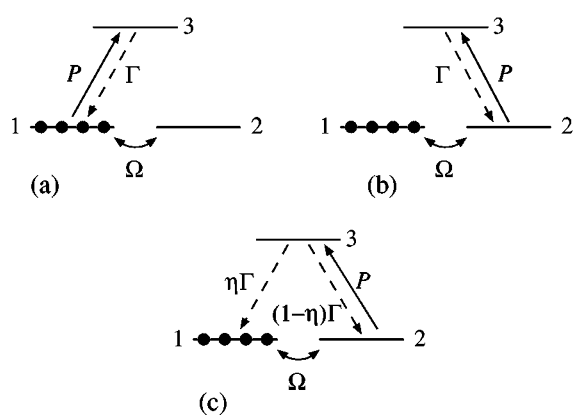

FIG. 2. Optical pumping schemes suppressing the transition from level 1 to level 2. Levels 1 and 2 are coupled via coherent interaction Ω. The solid arrow represents optical excitation (P) to level 3 and the dashed arrow represents the decay (Γ) to the ground levels.

$$\left.\frac{d\rho_{11}}{dt}\right|_{\text{pump}} = \eta P \rho_{22}, \tag{10}$$

exists. This term, however, is ineffective because $\rho_{22} \sim 0$ owing to the Zeno effect.

V. CONCLUDING REMARKS

We have shown that one can control the spin motion by repetitive or continuous optical pumping without photon absorption. The phenomenon can be understood in terms of the quantum Zeno effect and the interaction-free measurement. This pumping scheme might be of no practical importance because recycling of the transmitted photons is not easy in usual circumstances and also because the effect is easily masked by the intrinsic spin relaxation as shown in Sec. III. But it would not diminish the conceptual importance of the present scheme.

Another merit of the spin system under consideration is that it could be a clear example of the inverse Zeno effect because we can drag the spin direction just by redirecting the pumping beam. In general, more complicated series of measurements have to be devised to define the trajectory followed by the system. It also helps to clarify the relation to the adiabatic following of the spin to the slowly rotating magnetic field [8].

Finally we will estimate the experimental parameters to demonstrate the absorption-free spin manipulation. In order to satisfy the necessary conditions for the Zeno effect, $p = P/\Gamma \gg 1, \omega = |\Omega|/\Gamma \gg 1$, small Γ is preferable (see Fig. 1). For alkali atoms in a vapor cell, the spin relaxation rate is about $100 \mathrm{s}^{-1}$ and is rather large for the present purpose. But for laser-cooled, trapped atoms, it can be reduced down to $\Gamma \sim 1 \mathrm{~s}^{-1}$. If we use a mechanical beam steering, $\Omega \sim 100$ Hz or $\omega \sim 100$ would be feasible. The typical pumping rate is given as $P \sim (I/\mathrm{mW}) \times 10$ kHz, for the laser beam power I, therefore even with a small diode laser generating $I = 1$ mW, we can have $p \sim 10^5$. An atomic cloud cooled in a trap has enough optical density, which enables us to measure the photoabsorption precisely to verify Eq. (6). We may have to turn off the lasers and the magnetic fields for the trap.

We are carrying out an experiment demonstrating the absorption-free optical pumping and have obtained some preliminary results. The details will be reported elsewhere.

ACKNOWLEDGMENTS

We acknowledge valuable discussions with W. Happer, T. Yabuzaki, and W.D. Phillips. This research was supported by the Ministry of Education, Science, Sports and Culture in Japan, under a Grant-in-Aid for Scientific Research.

[1] See, for example, W. Happer, Rev. Mod. Phys. **44**, 169 (1972).
[2] B. Misra and E. C. G. Sudarshan, J. Math. Phys. **18**, 756 (1977).
[3] W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A **41**, 2295 (1990).
[4] V. Frerichs and A. Schenzle, Phys. Rev. A **44**, 1962 (1991).
[5] E. Block and P. R. Berman, Phys. Rev. A **44**, 1466 (1991).
[6] Y. Aharonov and M. Vardi, Phys. Rev. D **21**, 2235 (1980).
[7] T. P. Altenmüller and A. Schenzle, Phys. Rev. A **48**, 70 (1993).
[8] M. Kitano, Phys. Rev. A **56**, 1138 (1997).
[9] P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M.A. Kasevich, Phys. Rev. Lett. **74**, 4763 (1995).
[10] M. Porrati and S. Putterman, Phys. Rev. A **36**, 929 (1987).