Displacement of a Laser Beam by a Precessing Magnetic Dipole

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Exchange of angular momentum between photons and atoms cannot only cause optical pumping, but also a lateral displacement of a laser beam traveling through a homogeneous atomic vapor. We present experimental data from the ground state of atomic sodium demonstrating this effect.

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The possibility of optically pumping an atomic medium [1] was predicted on the basis of a detailed analysis of the conservation of angular momentum during absorption of a photon by an atom [2]. While this early theoretical [1] and experimental [3] work dealt exclusively with the modification of the sublevel *populations*, it was shown later, in the "quantum theory of optical pumping" [4], that also *coherences* between ground-state sublevels are affected by the optical pumping process. The effect of the pump field on the sublevel coherences is twofold: A damping process reduces their lifetime and a virtual level shift causes a coherent evolution. Physically, coherences between angular momentum substates correspond to angular momentum components perpendicular to the quantization axis; the modification of the sublevel dynamics changes therefore the atomic angular momentum. Since the total angular momentum is a conserved quantity, this change of the atomic contribution must be compensated by a change of the angular momentum of the radiation field, as was first realized by Happer and co-workers [5,6].

For a brief discussion of the exchange of angular momentum between the atomic system and the radiation field, we consider an atomic system with an allowed transition between a $J=\frac{1}{2}$ ground state and a $J'=\frac{1}{2}$ excited state (see Fig. 1). The population difference $\rho_{22}-\rho_{11}$ and the coherences ρ_{12} and ρ_{21} between the two ground-state sublevels correspond to the longitudinal and transverse components of the angular momentum vector $\mathbf{m}=\{\rho_{12}+\rho_{21}, -i(\rho_{12}-\rho_{21}), \rho_{22}-\rho_{11}\}$. Polarized light propagating through this medium parallel to the quantization axis can couple to the two transitions indicated by the dashed arrows. In a dilute atomic vapor with an optical susceptibility $\|\chi\| \ll 1$, the complex index of refraction of the medium does not depend on the transverse components m_x and m_y of the atomic angular momentum, implying that they cannot cause a modification of amplitude or polarization of the field. Quantum mechanically this means that the photon spin is not modified by the interaction with the transverse components of the angular momentum. The change in the atomic angular momentum must therefore be compensated by a different mechanism; specifically, it is accompanied by a change in the orbital angular momentum of the photons, $\mathbf{r}\times\hbar\mathbf{k}$, where $\mathbf{k}$ represents the wave vector, $\hbar\mathbf{k}$ the linear momentum of the photon, and $\mathbf{r}$ its position [5]. In a coordinate system with the z axis along the direction of the laser beam, a transfer of one quantum of angular momentum in the x (y) direction to every photon in the laser beam leads therefore to a lateral displacement of the laser beam by a distance $d=1/|\mathbf{k}|$ in the $-y$ (x) direction.

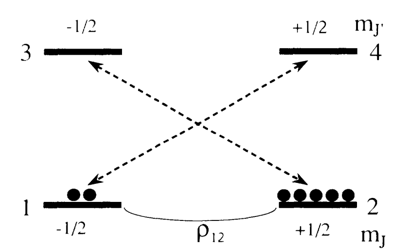

FIG. 1. Schematic representation of the model for the atomic system.

As the modification of the transverse atomic angular momentum by the interaction with the laser beam includes contributions from the damping of the sublevel coherences as well as from the light-shift effect, it is also possible to distinguish two contributions to the beam displacement compensating for these effects. The damping of an atomic angular momentum oriented, e.g., along the y axis, must be compensated by an increase of the y component of the external angular momentum of the photons. In direct proportion to the damping of m_y, the laser beam should therefore experience a displacement in the x direction. Like the damping effect, this beam displacement should have an absorptionlike dependence on the detuning of the laser frequency from the optical resonance, independent of the polarization of the light.

The light-shift effect, on the other hand, causes a rotation of the angular momentum around the direction of propagation of the laser beam. If the atomic angular momentum is initially oriented along the y axis, the light-shift effect corresponds to a transfer of angular momentum in the x direction from the radiation field to the atomic medium. The laser beam should therefore be displaced in the y direction. Like the light shift itself, this displacement should be antisymmetric with respect to the laser detuning and change sign when the polarization of the light changes between opposite circular polarizations.

The experimental setup used for the verification of the effect is shown schematically in Fig. 2. For the atomic medium, we used Na vapor which was heated to a temperature of 124 °C, resulting in an absorption at the center of the resonance line of 40%. 200 mbar of argon was added as a buffer gas, both to make the optical resonance line homogeneous and to increase the time which the atoms spent inside the laser beam. A nonvanishing angular momentum was created in the sample by optical pumping. For a sensitive detection of the beam displacement, it proved useful to make the atomic angular momentum time dependent, thereby modulating the position of the laser beam. For this purpose, we used polarization modulation of the pump laser beam in the presence of a transverse magnetic field [7]. If the modulation frequency is close to the Larmor frequency in the applied magnetic field, the net effect of this excitation scheme is the creation of a ground-state magnetization [8] precessing around the magnetic field. The beam displacement caused by the y component of the magnetization (see Fig. 2 for the definition of the coordinate system) was then modulated at the Larmor frequency.

In order to measure the beam displacement, we used a second laser beam derived from the same laser. This probe beam was passed through a single mode optical fiber in order to eliminate fluctuations of the beam position originating in the dye laser. For a precise measurement of the beam position, we used a quadrant photodiode (Hamamatsu model S4349) with a homebuilt amplifier (bandwidth ~ 1 MHz) and focused the beam into the center of the four diodes, so that the signal from the detector vanished if the sample was not optically pumped. In order to minimize spurious signals due to scattered light from the pump beam falling on the detector, we used counterpropagating beams, as shown in Fig. 2. The intensity of the probe beam was 0.9 mW/cm^2, the intensity of the pump beam 9 mW/cm^2. The two beams overlapped in the sample cell at an angle of $\sim 0.5°$. In order to create a homogeneous optically pumped medium across the probe beam profile, the pump laser beam was passed through a spatial filter before the sample cell (not shown in the figure) and expanded to twice the diameter of the probe beam (9 mm versus 4 mm).

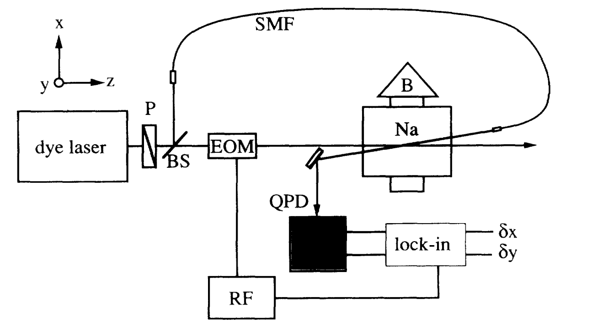

FIG. 2. Experimental setup for measurement of the beam displacement. P, polarizer; BS, beam splitter; EOM, electro-optic modulator; SMF, single-mode fiber; QPD, quadrant photodiode; B, magnetic field; RF, radio frequency synthesizer.

The detector provides two signals which are proportional to the position of the laser beam, measured from the center of the detector. These signals were passed through a lock-in amplifier whose reference frequency was equal to the modulation frequency and therefore to the precession frequency of the atomic magnetic dipole. For the measurements reported here, this frequency was set on resonance with the Larmor frequency of 100 kHz and the reference phase of the lock-in amplifier was set to $\pi/2$ in order to select signal contributions proportional to the y component of the magnetization. The resulting signal is shown in Fig. 3 as a function of the laser frequency:

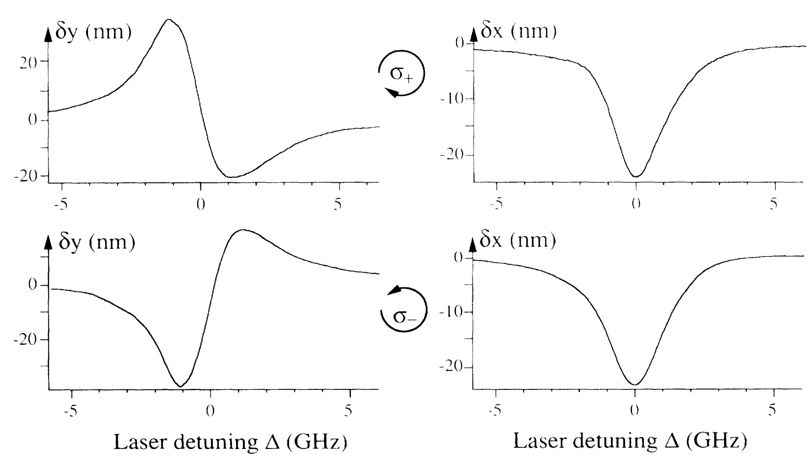

FIG. 3. Experimentally measured beam displacement. Shown is the amplitude of the signal at the Larmor frequency, out of phase with respect to the intensity modulation perpendicular (left) and parallel (right) to the magnetic field as a function of the laser frequency. The upper row was measured with a right circularly polarized probe beam; the lower row, with a left circular polarization.

The amplitude of the displacement in the y direction, shown on the left-hand side, exhibits the predicted dispersionlike dependence on the laser frequency. The width of the resonance line is determined by the width of the pressure-broadened D_1 transition. Comparison of the upper and lower traces shows that if the polarization of the probe beam is changed between opposite circular polarizations, the displacement changes sign. The corresponding signals for the x direction (parallel to the magnetic field) are shown on the right-hand side. In this case, the displacement amplitude has an absorptionlike dependence on the laser frequency detuning and is independent of the probe beam polarization, as expected. The signal was calibrated with the same experimental setup by generating the beam displacement with a piezomounted mirror. From this calibration, the maximum amplitude of the displacement was determined as $23.5(\pm 5)$ nm.

For a comparison of these experimental results with the theoretically predicted behavior, we treat the probe laser beam as a classical electromagnetic wave propagating through the polarized atomic medium. In this context, the beam displacement can be understood as being due to the breaking of the rotational symmetry of the system by the presence of the transverse magnetization. If the optical susceptibility is small, $\|\chi\| \ll 1$, the eigenpolarizations of a plane wave are proportional to [9]

$$\begin{pmatrix} E_{x0} \\ E_{y0} \\ E_{z0} \end{pmatrix}_{\pm} \cong \begin{pmatrix} 1 \\ \pm i \\ \chi_0(\mp m_x - i m_y) \end{pmatrix}, \tag{1}$$

where χ_0 is the susceptibility of the unpolarized medium. Thus, the field has a longitudinal component proportional to the transverse component of the sublevel polarization. The corresponding Poynting vector is then no longer parallel to the z axis; in terms of the real and imaginary parts of $\chi_0 = \chi_0' + \chi_0''$, its transverse components are proportional to

$$\begin{pmatrix} S_{x0} \\ S_{y0} \end{pmatrix}_{\pm} \alpha \pm \chi_0' \begin{pmatrix} m_x \\ m_y \end{pmatrix} + \chi_0'' \begin{pmatrix} -m_y \\ m_x \end{pmatrix}, \tag{2}$$

where the two signs refer to the two eigenpolarizations. The transverse angular momentum leads therefore to a beam displacement in the direction of the atomic angular momentum with a dispersive frequency dependence and a displacement in the orthogonal direction with an absorptive frequency dependence. The optical pumping scheme described above produces a time-dependent magnetization

$$\mathbf{m}(t) = \{m_{x\infty},\, m_{y\infty}\cos(\omega_m t) - m_{z\infty}\sin(\omega_m t),\, m_{y\infty}\sin(\omega_m t) + m_{z\infty}\cos(\omega_m t)\}, \tag{3}$$

with steady-state ground-state magnetization in the rotating frame

$$\mathbf{m}_\infty = \frac{P_+}{\gamma_{\text{eff}}(\Omega_L^2 + \bar{\Delta}^2 P_+^2 + \gamma_{\text{eff}}^2)} (\bar{\Delta} P_+ \Omega_L,\, -\gamma_{\text{eff}}\Omega_L,\, \bar{\Delta}^2 P_+^2 + \gamma_{\text{eff}}^2). \tag{4}$$

Here, the optical pumping rate is defined as $P_+ = \omega_1^2/4\Gamma_2(1+\bar{\Delta}^2)$ in terms of the optical dephasing rate Γ_2, the optical Rabi frequency ω_1, and the normalized optical detuning $\bar{\Delta} = \Delta/\Gamma_2 = (\omega_{\text{laser}} - \omega_0)/\Gamma_2$ of the laser frequency ω_{laser} with respect to the optical transition frequency ω_0. The other parameters in Eq. (4) are the effective ground-state relaxation rate $\gamma_{\text{eff}} = \gamma_0 + P_+$, which is the sum of the diffusion loss rate γ_0 and the optical pumping rate P_+, and the Larmor frequency $\Omega_L = B\mu_B g/\hbar$, expressed in terms of the strength of the magnetic field B, Bohr's magneton μ_B, and the Landé factor g. Since this magnetization precesses around the transverse magnetic field at the modulation frequency ω_m, the displacement of the laser beam should be time dependent with a period equal to the Larmor period.

With the setup used, the intensity is therefore modulated at the Larmor frequency and we expect an overall signal

$$\begin{pmatrix} s_x \\ s_y \end{pmatrix}_{\pm} \cong \left[l \begin{pmatrix} \pm\chi_0' m_x - \chi_0'' m_y \\ \chi_0'' m_x \pm \chi_0' m_y \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \right] \exp\left[-i\frac{l\omega}{c}\left(1 + \chi_0 \frac{1 \mp m_z}{2}\right)\right]. \tag{5}$$

The first term in the square bracket is the beam displacement which we want to measure, while the second term takes deviations of the average laser beam position from the true center of the detector into account. Figure 4 shows the beam displacement calculated according to Eqs. (3)–(5) on optical resonance as a function of time, using parameters appropriate for our experimental system: $\chi_0 = 5\times10^{-6}$, $P_+ = 10^4\ \text{s}^{-1}$, $\Gamma_2 = 1.2\times10^{10}\ \text{s}^{-1}$, $x_0 = y_0 = 0$, and $l = 4$ cm. The roughly sinusoidal time dependence of the beam displacement reflects the proportionality to the y component of the angular momentum while the deviations are due to the modulation of the transmitted intensity.

This expression can be simplified if we consider an optically thin medium and eliminate terms that are time independent or higher harmonics of the Larmor frequency. Taking only signal contributions at the Larmor frequency into account is primarily an experimental convenience, since it allows us to use a lock-in detection and eliminate slow fluctuations of the laser beam position due to mechanical or thermal instabilities. With these simplifications, we get

$$\begin{pmatrix} s_x \\ s_y \end{pmatrix} \cong l m_y \begin{pmatrix} -\chi_0'' \\ \pm\chi_0' \end{pmatrix} + \left[\begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + l m_x \begin{pmatrix} \pm\chi_0' \\ \chi_0'' \end{pmatrix} \right] \exp\left[-i\frac{l\omega}{c}\left(1 + \chi_0 \frac{1 \mp m_z}{2}\right)\right]. \tag{6}$$

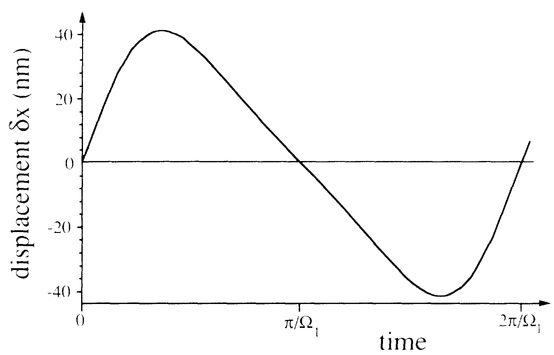

FIG. 4. Calculated time dependence of the beam displacement parallel to the magnetic field.

The modulation of the transmitted intensity makes therefore also those signal components time dependent that are due to a time-dependent displacement of the laser beam from the center of the photodiode. In our experiments, we have taken care to eliminate these contributions, not only by adjusting the position of the laser beam as close as possible to the center of the detector, but also via the different time dependence of the two contributions; while the total intensity of the beam and therefore the second term of the signal depend on m_z, the beam displacement varies with m_y. If the modulation frequency is on resonance with the Larmor frequency, the beam displacement is therefore 90° out of phase with respect to the driving signal, while the second term is in phase, as is evident from Eq. (3). As described in the experimental section above, we used this phase dependence to separate the displacement signal from unwanted signal contributions due to the unavoidable misalignment of the laser beam. The experimentally measured lock-in signal can be obtained by Fourier transformation. The result is in good qualitative agreement with the behavior observed in the actual experiment.

The beam displacement reported here may be compared to the "magnetic displacement of a laser beam" [10] that can be observed when resonant light is transmitted through an atomic vapor. While the experimental setup and the size of both effects are comparable, the underlying physics are quite different: While the effect reported here is due to a transfer of angular momentum between atoms and photons, the "magnetic displacement" leaves the atomic medium always close to equilibrium. The atomic angular momentum remains therefore zero and there is no transfer between the two partial systems. The size of the magnetic displacement is proportional to the strength of the magnetic field, while the amplitude of the displacement by the transverse magnetic moment is independent of the magnetic field strength.

In conclusion, we have shown that the conservation of angular momentum during the interaction of light with atomic multilevel systems can lead to a displacement of a laser beam propagating through an optically pumped medium. The displacement includes contributions that are proportional to the absorption and to the dispersion of the unpolarized medium and to the angular momentum components perpendicular to the laser beam. For a fully polarized medium, the size displacement is of the order of the optical wavelength times the ratio between sample length and absorption length.

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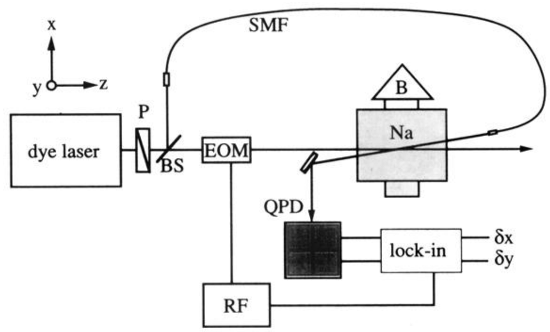
[1] A. Kastler, J. Phys. (Paris) **11**, 255 (1950).
[2] A. Kastler, Science **158**, 214 (1967).
[3] W. B. Hawkins, Phys. Rev. **98**, 478 (1955).
[4] J. P. Barrat and C. Cohen-Tannoudji, J. Phys. Radium **22**, 329 (1961); **22**, 443 (1961).
[5] W. Happer and B. S. Mathur, Phys. Rev. Lett. **18**, 577 (1967).
[6] G. Moe and W. Happer, J. Phys. B **10**, 1191 (1977).
[7] H. Klepel and D. Suter, Opt. Commun. **90**, 46 (1992).
[8] D. Suter and J. Mlynek, Phys. Rev. A **43**, 6124 (1991).
[9] D. Suter, Opt. Commun. **86**, 381 (1991).
[10] A. Weis and R. Schlesser, Verh. Dtsch. Phys. Ges. **26**, 819 (1991).



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