Alignment-to-orientation conversion in the ground state of atomic Cs with linearly polarized laser excitation

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In this study we explored the angular momentum alignment-to-orientation conversion occurring in various alkali metals – K, Rb, Cs. We used a theoretical model that is based on Optical Bloch equations and uses the density matrix formalism. Our model includes the interaction of all neighboring hyperfine levels, the mixing of magnetic sublevels in an external magnetic field, the coherence properties of the exciting laser radiation, and the Doppler effect. Additionally we simulated signals where the ground- or the excited-state coherent processes were switched off allowing us to determine the origins of obtained signals. We also performed experiments on Cs atoms with two laser beams: linearly polarised Cs $D_1$ pump and circularly polarized Cs $D_2$ probe. We used the pump beam to create angular momentum alignment in the ground state and observed the transmission signal of the probe beam as we changed the magnetic field. Full analysis of the experimentally obtained transmission signal from a single circularly polarized probe laser component is provided.

I. INTRODUCTION

The Hanle effect [1], non-linear magnetooptical rotation [2], electromagnetically induced transparency (EIT) [3] and other magnetooptical (MO) effects [4] have been previously studied and have led to advances in the development of extremely sensitive magnetometers [5, 6], atomic clocks [7], optical switches [8] and isolators [9]. One such MO effect is the alignment-to-orientation conversion (AOC) of angular momentum spatial distribution.

An aligned state is created when an ensemble of atoms absorbs linearly polarized light. If the $\mathbf{E}$ vector of linearly polarized light coincides with the quantization axis $z$, here assumed to be parallel to the external magnetic field $\mathbf{B}$, it creates a longitudinal alignment, meaning that the populations of the magnetic sublevels $+m_F$ and $-m_F$ are equal, but can have different values depending on the $|m_F|$ quantum number. But if the $\mathbf{E}$ vector of linearly polarized light is perpendicular to the quantization axis, then a transverse alignment of the angular momentum is created which implies that there is coherence between magnetic sublevels with quantum numbers that differ by $\Delta m_F = \pm 1$.

The symmetry of an initially aligned state can be changed with some additional perturbation, and when this change leads to the creation of angular momentum orientation it is called alignment-to-orientation conversion. AOC has been achieved with magnetic field gradient [10] and anisotropic collisions [11–13]. Another common way to realise AOC is to use an external electric field [14, 15]. In contrast to the electric field, an external magnetic field cannot cause AOC, because it is an axial field and has even parity. Therefore some additional circumstances are required. These circumstances are fulfilled when the interaction of the atoms with the magnetic field is comparable to the hyperfine interaction within the atom, thereby causing AOC [10]. The conversion from an initially oriented state to an aligned state is also possible [17].

The angular momentum transformation from an initially aligned state to a transverse-orientation can be achieved by, first, setting the linearly polarized excitation in an angle of $\pi/4$ with respect to the quantization axis (FIG. 3) so that it can be split into a linear and two circular polarization components. Second, it is necessary to apply the external magnetic field so that the conditions for the hyperfine Paschen-Back effect is fulfilled and the dependence of the energies of the magnetic sublevels is non-linear (FIGs. 1, 2). When all three optical components of light polarization are present the coherent excitation of $\Delta m_F = \pm 1$ is possible which leads to the creation of angular momentum transverse orientation.

Previously AOC in an external magnetic field was studied in various atoms [18–21] and with a focus on the change of angular momentum distribution in the excited state [16–22]. Recently AOC has been studied also in the ground-state of rubidium atoms [23].

The aim of this study is to further explore the ground-state AOC. In this study we propose to create AOC in the ground state by means of an external magnetic field and a strong linearly polarized pump beam, while observing the
change of angular momentum orientation as a function of the external magnetic field by probing the pumped atoms with a weak circularly polarized laser.

First, we will present and discuss some results of modeled signals for AOC in the ground state of alkali atoms: K, Rb and Cs. Second, we studied the influence of ground- and excited-state coherences on these signals. Third, we obtained preliminary experimental results and provided a clear interpretation of the observed signals.

FIG. 2. Frequency shifts of the magnetic sublevels \( m_F \) of the excited-state fine-structure level 6\(^2\)P\(_{1/2} \) as a function of magnetic field for \(^{133}\)Cs. Zero frequency shift corresponds the excited-state fine-structure level 6\(^2\)P\(_{1/2} \).

FIG. 1. Frequency shifts of the magnetic sublevels \( m_F \) of the excited-state fine-structure level 6\(^2\)P\(_{1/2} \) as a function of magnetic field for \(^{133}\)Cs. Zero frequency shift corresponds to the ground-state fine-structure level 6\(^2\)S\(_{1/2} \).

II. THEORETICAL MODEL

The theoretical model that we used is based on the Liouville or optical Bloch equations (OBEs) for the density matrix \( \rho \). The density matrix is written in the basis of hyperfine levels both in the ground and excited state, including the whole manifold of hyperfine levels \( | \xi, F_i, m_{F_i} \rangle \), where \( F_i \) refers to the quantum number of the hyperfine angular momentum component in the ground \( (i = g) \) or the excited \( (i = e) \) state, \( m_{F_i} \) denotes the respective magnetic quantum number and \( \xi \) represent all the other quantum numbers that are not essential for the current study.

We describe the time evolution of the density matrix using the optical Bloch equations

\[
\ih \frac{\partial \rho}{\partial t} = [\hat{H}, \rho] + \ih R \rho,
\]

where \( \hat{H} \) is the total Hamiltonian operator of the system and \( \hat{R} \) is the relaxation operator. The full Hamiltonian can be written as \( \hat{H} = \hat{H}_0 + \hat{H}_B + \hat{V} \), where \( \hat{H}_0 \) is the unperturbed system Hamiltonian, \( \hat{H}_B \) describes the interaction with the external magnetic field, and \( \hat{V} = -\mathbf{d} \cdot \mathbf{E}(t) \) is the operator that describes the atom-laser field interaction in the electric dipole approximation. The operator includes the electric field of the exciting light \( \mathbf{E}(t) \) and an electric dipole operator \( \mathbf{d} \).

As we use continuous laser excitation, we calculate the density matrix for steady state conditions

\[
\frac{\partial \rho_{g_i, g_j}}{\partial t} = \frac{\partial \rho_{e_i, e_j}}{\partial t} = 0,
\]

where \( \rho_{g_i, g_j} \) and \( \rho_{e_i, e_j} \) are density matrix elements for the ground and excited-state. This condition reduces the differential equations to a system of linear equations. The explicit form of these equations and the description of terms appearing in these equations can be found in [23, 25].

The polarization moments (multipole moments) can be expressed in terms of the density matrix elements
\[ \rho_{m'm} = \sum_{m'm'} \langle F_{m'm'} | F_{m'} \rangle \rho_{m'm}, \tag{3} \]

where \( \rho^e \) is the co-variant component of multipole moments, \( k \) is the rank of the polarization operator with \( 2k + 1 \) components \( \kappa = -k, \ldots, k \). From Eq. \( 3 \) we can determine that the amount of angular-momentum orientation \( \rho^e \) is constructed from the first off-diagonal (second diagonal, next diagonal) elements in the calculated density matrix which correspond to \( \Delta m_F = \pm 1 \) coherences.

To compare the model calculations with experimentally measured signals we need to average over the Doppler profile.

To probe the ground state, we can calculate absorption of left and right circularly polarized laser tuned to \( D_2 \) line. It is assumed that the probe beam is much weaker than the pump beam, so that it does not disturb the prepared state. The absorption of the weak probe beam of polarization \( \mathbf{e}_{\text{probe}} \) is calculated as

\[ A(\mathbf{e}_{\text{probe}}) = \tilde{A}_0 \sum_{e_i g_j} \frac{d^2_{e_i g_j} \rho_{g_i g_k} d_{g_k e_j}}{\Delta^2_{e_i g_j} + \Gamma^2_R}, \tag{4} \]

where \( d^2_{e_i g_j} = \langle e_k | \hat{d} \cdot \mathbf{e}_{\text{probe}} | g_i \rangle \) are the dipole transition matrix elements for the radiation with specific polarization \( \mathbf{e}_{\text{probe}} \). \( \tilde{A}_0 \) is the constant of proportionality. The detuning from resonance \( \Delta_{e_i g_j} \) is expressed as:

\[ \Delta_{e_i g_j} = \tilde{\omega} - \omega_{e_i g_j}, \tag{5} \]

\( \tilde{\omega} \) is the laser frequency and \( \omega_{e_i g_j} \) is energy difference between magnetic sublevels \( |e_i\rangle \) and \( |g_j\rangle \).

The absorption width is defined by relaxation rate \( \Gamma_R \)

\[ \Gamma_R = \frac{\Gamma + \Delta \omega}{2}, \tag{6} \]

which is influenced by transit relaxation rate \( \gamma \), the rate of spontaneous transitions \( \Gamma \) and spectral width \( \Delta \omega \) of laser radiation.

The average transit relaxation rate \( \gamma \) can be expressed as

\[ \gamma = \frac{\nu_{th}}{d}, \tag{7} \]

where \( \nu_{th} \) is the thermal velocity of atoms and \( d \) is the laser beam diameter. In the calculation the transit relaxation was assumed to be the same for both processes: pumping and probing.

The reduced Rabi frequency of pumping beam was estimated as

\[ \Omega_R = \frac{|d| \cdot |\epsilon|}{\hbar} = \frac{|d|}{\hbar} \frac{2\gamma}{\epsilon_0 nc}, \tag{8} \]

where \( |d| = 4.231 \epsilon a_0 \) is the reduced dipole matrix element for the \( D_1 \) transition, \( \epsilon \) is the electron charge, and \( a_0 \) is the Bohr radius \( [27] \). The quantity \( I \) is the power density (directly related to the amplitude of the electric field \( |\epsilon| \)), \( \epsilon_0 \) is the electric constant, \( n \) is the refractive index, and \( c \) is the speed of light.

### III. EXPERIMENT

To create the pump-probe geometry (FIG.3), we built an experimental set-up whose side-view is shown in figure 4. We placed a 2.5x2.5 cm cylindrical pyrex Cs vapor cell between the ferromagnetic cores of an electromagnet (EM). The spacing between the poles was 4.3 cm. The inhomogeneity of the field in the center of the poles was estimated to be no more than 0.027 % by a finite-element electromagnetic field solver, based on the geometry of the magnet. The current for the electromagnet was supplied by a bipolar power supply, and the symmetrical triangular current scan was generated by a function generator. The frequency of the magnetic field scan was 2.00 mHz with a maximum scan amplitude resulting in a magnetic field range from \(-3100 \text{ to } +3100 \text{ G} \).

The atoms in the cesium vapor cell were pumped to the excited state \( 6P_{1/2} \) by a linearly polarized light of a DPSS Ti:Sapphire laser (SolsTiS from M Squared) with a wavelength of 895 nm (\( D_2 \) line of Cs) and probed with a circularly polarized light of a tuneable, grating-stabilized external-cavity single-mode diode laser DL 100 (Toptica AG) with a wavelength of 852 nm (\( D_1 \) line of Cs).

The beam of the \( D_1 \) laser was expanded in the \( x \) direction by a pair of anamorphic prisms (APP). The elliptically shaped beam dimensions were measured by a beam profiler. The semi-major axis was 3 mm, and the semi-minor axis was 1 mm as measured of a Gaussian fit. The laser beam was directed to the cesium vapor cell so it would enter the cell at a \( \pi/4 \) angle with respect to the magnetic field direction.
The $D_2$ laser frequency was fixed to a saturation absorption spectrum (SAS) signal. A dedicated feedback controller (Digilock by Toptica AG) managed the laser’s temperature and current controllers to lock the laser to a particular peak of the SAS. During the experiments the frequency of the laser was monitored by the HighFinesse WS/7 Wavemeter. The probe laser power was attenuated using a half-wave Fresnel rhomb retarder followed by a linear polarizer and neutral density filters. An achromatic quarter wave plate ($\lambda/4$) was used to convert the linearly polarization of the probe beam into circularly polarized probe laser radiation.

The transmission signal was detected with a Thorlabs SM1PD1A photodiode (PD). The photodiode was placed at the end of a tube which also contained a convex lens and a shortpass filter. The signal from the photodiode was amplified by a transimpedance amplifier with a gain of $10^6$, followed by a voltage amplifier with a gain of $10^4$.

Every scan was acquired with an Agilent DSO5014A digital oscilloscope and transferred to a PC with a minimum of 16 scans in total for each component.

The measured transmission signals were averaged over multiple scans. When comparing the experimental signals to signals obtained from the theoretical calculations, a constant background was subtracted before the signals were normalized to the maximum of each component.

IV. RESULTS & DISCUSSION

Absorption signals can provide a more direct measurement of the ground-state AOC when compared to the fluorescence signals, as the latter is commonly associated with effects occurring in the excited state. First we wanted to establish how the ground-state AOC would appear in different atoms, subsequently allowing us to determine the most suitable element to concentrate our experimental efforts on.

Figure 5 shows the modeled results of absorption signals from alkali metal elements – K, Rb and Cs. The left section (FIG. 5 (a), (d)) shows the absorption signals from K atoms, middle section (FIG. 5 (b), (e)) – from Rb and the right section (FIG. 5 (c), (f)) – from Cs atoms. The pairs of hyperfine transitions for the pump and probe beams of the modeled signals that exhibited the highest values in the absorption difference signals and allowed to (better) set apart the ground-state coherences from the excited-state coherences are indicated at the top of Figure 5.

In order to distinguishing between the features in the signal caused by ground-state and excited-state coherent effects we set the non-diagonal density matrix elements to zero. We do this by increasing the relaxation rate $\gamma_{\text{non-diagonal}}$ of only these elements with the ratio of $\gamma_{\text{non-diagonal}}/\gamma_{\text{diagonal}} = 10^9$ with respect to the $\gamma_{\text{diagonal}}$ which is the normal transit relaxation rate experienced by diagonal elements (this is left unchanged). This allows us to observe the influence of transfer of coherences from the ground state to the excited state (and vice versa). The bottom section of Figure 5 shows the comparison of the three different $\gamma_{\text{non-diagonal}}$ cases of simulated absorption difference signals. The green curve corresponds to the case when the ground-state coherent effects were set to zero, the orange curve – to the case when the excited-state coherent effects were set to zero and the blue curve – when all elements in the density matrix experience normal relaxation.

Figure 5 (d), (e) and (f) show the difference between two oppositely circularly polarized absorption components of the probe beam. K shows the highest value of relative absorption difference (FIG. 5 (d)) out of all three elements shown here. Nevertheless, we deem K atoms not suitable for measurements, because magnetic field region where the excited- and ground-state coherences are created are very close to each other in terms of magnetic field, thus the subsequent analysis and interpretation of these signals could prove cumbersome. The absorption difference signal of Rb atoms appears to be almost entirely connected with the ground-state coherent effects, as can be seen from the small differences between the blue and orange curves (FIG. 5 (e)). But the amplitude of the Rb absorption difference signal is the smallest of the three. The difference between the normal relaxation (FIG. 5 (f) blue) and the excited-coherence-fast relaxation (FIG. 5 (f) orange) curve shows that the absorption difference signals of Cs atoms are quite strongly influenced by both the excited- and ground-state coherences at low and intermediate magnetic field values, but after approximately 1000 G the signal is almost entirely dependent on ground-state coherences. As a result we conclude that Cs is the most suitable element for observation of angular momentum AOC in the ground state.

Another parameter that the absorption signals depend on is the Rabi frequency. The results form numeric modeling showed that by increasing the Rabi frequency the absorption signal differences increased in amplitude and showed little change in shape. All modeled signals in Figure 5 have the same Rabi frequency $\Omega_R = 100$ MHz. Nevertheless, it should be noted that the necessary laser power values could differ between elements because of different dipole transition matrix element values associated with each element.

We included also the modeled individual circularly polarized absorption components in the upper part of Figure 5 because the interpretation of the origin of the observed signals is more easily understood and additional to emphasize the scale of the difference between the two absorption components. The amplitudes of the differences of the absorption components are about $10^3$ times smaller than the amplitudes of the individual circularly polarized absorption components.

Next we show the results of the experimentally measured transmission signal of a single circularly polarized absorption component. The signal from a single absorption component is shown because the two transmission signals are very similar. Figure 6 shows the transmission
FIG. 5. Numerical calculations of absorption for $^{39}$K, $^{85}$Rb and $^{133}$Cs. The first row: Circular component of absorption. The second row: the difference of circular ($\sigma^+$ and $\sigma^-$) components. In all case the Rabi frequency was $\Omega_R = 100$ MHz.

FIG. 6. Transmission signal of a single circularly polarized light component ($I_{L,\text{Probe}}$): Pump laser off: black dots—experimental data; red curve—theoretical data; Pump laser on: blue dots—experimental data; green curve—theoretical data.

signals when the frequency of the probe beam was fixed to the crossover peak from SAS signal corresponding to the $F_g = 4 \rightarrow F_e = (3; 5)$ transition.

When the pump beam is off we obtain the experimental transmission signal depicted by the black dots which is in agreement with the theoretical signal represented by the red line. The transmission signal rises (absorption decreases) as the magnetic field is increased. Initially a rather fast increase is observed, but after around 1000 G the slope of the increase diminishes. While the pump beam is off, notably also when the pump is on, a single interesting feature can be observed at 2800 G – a peak that shows a decrease in the transmission signal. The interpretation of the features appearing in the transmission signals (in FIG. 5) is given in figure 7. The dashed lines (in figure 7) represent the transition frequencies between pairs of magnetic sublevels from the Cs $D_2$ hyperfine manifold relative to the fixed probe laser frequency which corresponds to $\Delta \nu = 0$. The peak, that appears in the observed signal at 2800 G, is caused by two magnetic sub-levels ($m_{F_g}=3 \rightarrow m_{F_e}=4$) from the Cs $D_2$ hyperfine manifold coming into resonance with the probe beam, thus leading to an decrease in the transmission signal (an increase in the absorption signal). Next we switched the pump beam on and observed the change in the transmission signal. The obtained experimental transmission signal is depicted by the blue dots and the theoretical calculations are the solid green line in figure 8. In this case the frequency of the probe beam was fixed to the crossover peak of Cs $D_2 F_g = 4 \rightarrow F_e = (3; 5)$ transition, while the frequency of the pump beam was set to the Cs $D_1 F_g = 4 \rightarrow F_e = 3$ hyperfine transition. The overall tendency of the transmission signal to increase stayed the same. Nevertheless, noticeable changes in the trans-
mission signal occur in the region from 0 to 500 G and another broad structure at around 2000 G. The changes in the signal at the low field are strongly influenced by the processes in the excited state. Consequently, no further analysis of the low-magnetic-field changes in the transmission signal will be provided here at this point since we are mostly concerned with the ground-state AOC. The very broad feature appearing at around 2000 G is strongly connected with the ground-state processes. This feature is caused by the interaction of ground-state magnetic sublevels with both lasers. The solid lines in figure 7 correspond to the relative transition frequencies between two magnetic sublevels from Cs $D_1$ hyperfine manifold with respect to the probe laser frequency. When the solid lines of the Cs $D_1$ pump cross the dashed lines of the Cs $D_2$ probe an increase in the transmission signal can be observed. The transmission increases because the pump beam has emptied the ground-state magnetic sublevel population thereby the probe beam is not absorbed and the transmission increases.

The corresponding Rabi frequency of the theoretical transmission signal (FIG. 6 green solid line) was estimated from Eq. (8) and shows adequate agreement. The black solid curve in figure 7 corresponds to the theoretical absorption signal when the Rabi frequency is $\Omega_R = 5 MHz$ suggesting that the individual probe-pump resonances could be observed at lower power values of the pump beam. The three peaks appearing in the absorption signal (FIG. 6 black curve) could not be reproduced in our experiments. Probably because the volume containing the pumped atoms in the experiment was quite small when compared to the whole size of the cell while the theoretical modeling assumes that all the atoms experiencing the probe beam were pumped.

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[1] G. Moruzzi and F. Strumia, eds., *The Hanle effect and level-crossing spectroscopy* (Springer US, Boston, MA, 1991).
[2] D. Budker, W. Gawlik, D. F. Kimball, S. M. Rochester, V. V. Yashchuk, and A. Weis, Resonant nonlinear magneto-optical effects in atoms, *Rev. Mod. Phys.* **74**, 1153 (2002).
[3] S. E. Harris, Electromagnetically Induced Transparency, *Physics Today* **50**, 36 (1997).
[4] D. Budker and M. Romalis, Optical magnetometry (2007), [arXiv:0611246 [physics]](http://arxiv.org/abs/0611246).
[5] J. C. Allred, R. N. Lyman, T. W. Kornack, and M. V. Romalis, High-sensitivity atomic magnetometer unaffected by spin-exchange relaxation, *Phys. Rev. Lett.* **89**, 130801 (2002).
[6] V. Shah, G. Vasilakis, and M. V. Romalis, High bandwidth atomic magnetometer with continuous quantum nondemolition measurements, *Phys. Rev. Lett.* **104**, 013601 (2010).
[7] S. Knappe, P. D. D. Schwindt, V. Shah, L. Hollberg, J. Kitching, L. Liew, and J. Moreland, A chip-scale atomic clock based on $^{87}$Rb with improved frequency stability, *Optics Express* **13**, 1249 (2005).
[8] P. Yeh, Dispersive magneto-optic filters, *Applied optics* **21**, 2069 (1982).
[9] L. Weller, K. Kleinbach, M. Zentile, S. Knappe, I. Hughes, and C. Adams, Optical isolator using an atomic vapor in the hyperfine Paschen-Back regime., *Optics letters* **37**, 3405 (2012).
[10] Fano, Precession Equation of a Spinning Particle in Nonuniform Fields, *Phys. Rev.* **133**, B828 (1964).
[11] M. Lombardi, Note sur la possibilité d’orienter un atome par super-position de deux interactions séparément non orientantes en particulier par alignement électronique et relaxation anisotrope, Comptes rendus hebdomadaires des séances de l’Académie des sciences. Série B, Académie des sciences (Paris, France) **265**, 191 (1967).
[12] V. Rebane, Depolarization of Resonance fluorescence during Anisotropic Collisions, *Opt. Spectrosc. (USSR)* **24**, 163 (1968).
[13] T. Manabe, T. Yabuzaki, and T. Ogawa, Observation of Collisional Transfer from Alignment to Orientation of Atoms Excited by a Single-Mode Laser, *Phys. Rev. Lett.* **46**, 637 (1981).
[14] Lombardi, M., Création d’orientation par combinaison de deux alignements alignment et orientation des niveaux excités d’une décharge haute fréquence, *J. Phys. France* **30**, 631 (1969).
[15] M. Auzinsh, K. Bluhse, R. Ferber, F. Gaebauer, A. Jarmola, and M. Tamanis, Electric-field-induced symmetry
breaking of angular momentum distribution in atoms, 

Phy. Rev. Lett. **97**, 043002 (2006)

[16] J. Alnis and M. Auzinsh, Angular-momentum spatial distribution symmetry breaking in Rb by an external magnetic field, Phy. Rev. A **63**, 023407 (2001)

[17] H. Brändle, L. Grenacs, J. Lang, L. P. Roesch, V. L. Telegdi, P. Truttman, A. Weiss, and A. Zehnder, Measurement of the correlation between alignment and electron momentum in $^{12}$B $\to$ $^{12}$C(g.s.) decay by a novel technique: Another search for second-class currents, Phy. Rev. Lett. **40**, 306 (1978)

[18] Lehmann, Jean-Claude, Etude de l’influence de la structure hyperfine du niveau excité sur l’obtention d’une orientation nucléaire par pompage optique, J. Phys. France **25**, 809 (1964).

[19] W. E. Baylis, Optical-pumping effects in level-crossing measurements, Physics Letters A **26**, 414 (1968).

[20] J. C. Lehmann, Nuclear Orientation of Cadmium$^{111}$ by Optical Pumping with the Resonance Line $5^1S_0 - 5^1P_1$, Phy. Rev. **178**, 153 (1969).

[21] M. Krainska-Miszczak, Alignment and orientation by optical pumping with pi polarised light, Journal of Physics B: Atomic and Molecular Physics **12**, 555 (1979).

[22] M. Auzinsh, A. Berzins, R. Ferber, F. Gahlbauer, L. Kalvans, A. Mozers, and A. Spiss, Alignment-to-orientation conversion in a magnetic field at nonlinear excitation of the $D_2$ line of rubidium: Experiment and theory, Phy. Rev. A **91**, 053418 (2015).

[23] A. Mozers, L. Busaite, D. Osite, and M. Auzinsh, Angular momentum alignment-to-orientation conversion in the ground state of rb atoms at room temperature, Phy. Rev. A **102**, 053102 (2020).

[24] S. Stenholm, Foundations of Laser Spectroscopy (Dover Publications, Inc., Mineola, New York, 2005).

[25] K. Blushs and M. Auzinsh, Validity of rate equations for Zeeman coherences for analysis of nonlinear interaction of atoms with broadband laser radiation, Phy. Rev. A **69**, 063806 (2004).

[26] M. Auzinsh, D. Budker, and S. Rochester, Optically Polarized Atoms: Understanding Light-atom Interactions (OUP Oxford, 2010).

[27] M. Auzinsh, D. Budker, and S. M. Rochester, Light-induced polarization effects in atoms with partially resolved hyperfine structure and applications to absorption, fluorescence, and nonlinear magneto-optical rotation, Phy. Rev. A **80**, 053406 (2009).