New Mechanism for the Production of Optical Resonances with Subnatural Linewidths

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Optical resonances with subnatural linewidth as narrow as 2.6 MHz have been observed with excellent signal-to-noise ratio in the Na D_1 line (natural width 10 MHz) in a polarization spectroscopy experiment. The new, subnatural resonances arise from Zeeman coherences which are produced by a strong probe beam and destroyed by a velocity-selective optical Hanle effect.

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A reduction of the width of optical resonances below the limit imposed by the natural lifetime τ has been achieved in several experiments like radio-frequency–optical double resonance,[1] level crossing spectroscopy,[2] or, very recently, phase switching of a light field.[3] The classical Ramsey technique[4] and its optical analog with either time-delayed[5] or spatially separated light fields[6] can also provide signals narrower than the natural width. The idea of these methods is to produce a coherent interaction only with that fraction of atoms that are more long lived than the average.[7] Because of the exponential decay law this results in a loss of signal-to-noise ratio, which often cannot be outweighed by the improvement in the resolution. However, in cases where the full signal-to-noise ratio cannot be utilized because of systematic uncertainties regarding the line shape such narrowing techniques can result in a considerable improvement in the precision of the measurement.

In this Letter we report on a new mechanism, which leads to resonances considerably narrower than the natural width but which does not suffer from this reduction of the signal-to-noise ratio. Our method uses the technique of polarization spectroscopy[8,9] but in contrast to other experiments of this kind the probe beam perturbs the investigated medium about as strongly as the pump beam.

We consider the effect of this strong probe beam in a very simple atomic structure with a ground state $J_g = 1$ and an excited state $J_e = 0$ (Fig. 1). In such a situation new effects not considered in earlier work on polarization spectroscopy[8,10] appear: (i) The components E_+, E_- of the linearly polarized probe beam tend to equalize the populations of the $m = \pm 1$ sublevels altered by the circularly polarized pump beam E_s,[9] (ii) the E_+ and E_- components of the probe beam can create a coherence between the $m = \pm 1$ sublevels of atoms from all velocity classes, and (iii) the E_- component of the probe beam and the pump beam E_s create a coherence between the $m = \pm 1$ sublevels of atoms with the projected velocity $v = 0$. The effects (ii) and (iii) are associated with the Zeeman coherence ρ_{+-} and cannot be revealed as long as the sublevels $m = \pm 1$ are degenerate.[11] However, even in the absence of external magnetic or electric fields such a degeneracy can be removed if light shifts[12] of the appropriate energy levels are induced by the counterpropagating and differently polarized light beams. For an atom moving in such beams the energy shifts due to each light field are velocity dependent[13] and have different signs because of opposite Doppler detunings of the frequencies seen by the atom. Thus, the light shifts remove the degeneracy of the Zeeman sublevels and reveal the Zeeman coherence in a way similar to an external magnetic field.[14] This is in fact a new velocity-selective example of the optical Hanle effect,[15] where the parameter which changes the "optical Larmor frequency" ω_L (splitting of the Zeeman sublevels) is the atomic velocity v rather than the intensity

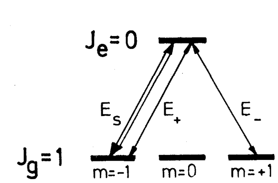

FIG. 1. Transitions induced by a circularly polarized pump beam (E_s) and a linearly polarized probe field (E_+, E_-).

of the light. Scanning of the laser frequency across the Doppler profile then picks up atoms from various velocity groups that bring different contributions of the Zeeman coherence to the probe beam signal. All population and coherence contributions interfere together if $v = 0$ and produce a narrow structure in the usual Doppler-free polarization spectroscopy signal, if the detuning from the exact resonance frequency is $\delta = 0$. A theoretical treatment also shows[16] that the $\rho_{+-}(\delta)$ dependence is resonant at $\delta = 0$ and narrower than the natural width if the intensities of the probe beam I_p and the pump beam I_s are not too large. The amplitude of the light field transmitted through a cell placed between crossed polarizers is composed of (1) a coherent background $T = \theta_0 + \theta$ which results from imperfection of the polarizers θ_0 and a small rotation θ from the exact 90° crossing position, and (2) two resonant terms: S arising from the population redistribution by the pump beam and s arising from the coherence introduced by the probe beam, which is also responsible for the velocity-selective optical Hanle effect. The intensity of the probe beam is[16]

$$I = I_0[T^2 + |S|^2 + |s|^2 + 2\theta_0(s^r + S^r) + 2\theta(s^r + S^r) + 2(s^r S^r + s^i S^i)], \qquad (1)$$

where I_0 denotes the intensity of the probe beam before passing the cell. The superscripts r and i designate the real and imaginary parts of the usual polarization spectroscopy signal S and the new coherence contribution s. In general, the function I describes a very complicated line shape, which is composed of Lorentzian and dispersion signals, but also contains the symmetrical and non-Lorentzian contributions $|s(\delta)|^2$ and $2(s^r S^r + s^i S^i)$ of subnatural width. However, this complicated line shape can be simplified to a large extent and made free from dispersion signals by simply adjusting θ to equal $-\theta_0$. Then the last term in Eq. (1) is the dominant subnatural-width contribution. This simplification is possible even if additional phase shifts, e.g., originating from birefringence of the cell windows, must be taken into account.

Experimental studies of the effects described above were performed on the sodium D_1 (589.6 nm) resonance line. Although the term structure is more complicated here than in the example discussed above, the arguments regarding the line shape still hold.[16] The experiments were carried out with a polarization spectroscopy setup and a frequency-stabilized, single-mode, dye ring laser. An important feature of the experimental arrangement (see Fig. 2) is that the linearly polarized probe beam and the circularly polarized pump beam travel collinearly (in opposite directions). In order to eliminate any influence of external fields that could obscure the velocity-selective optical Hanle effect, the cell was placed in a threefold Mumetal shield which reduced the magnetic field to less than 10^{-7} T.

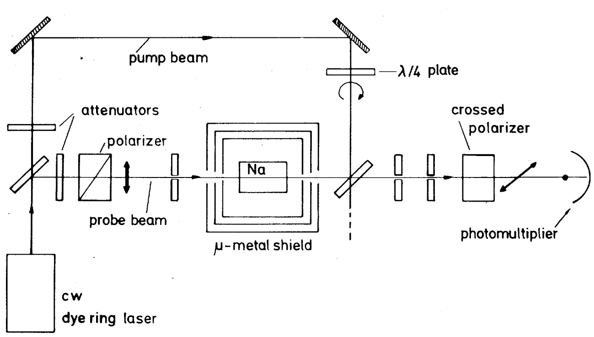

FIG. 2. Experimental arrangement.

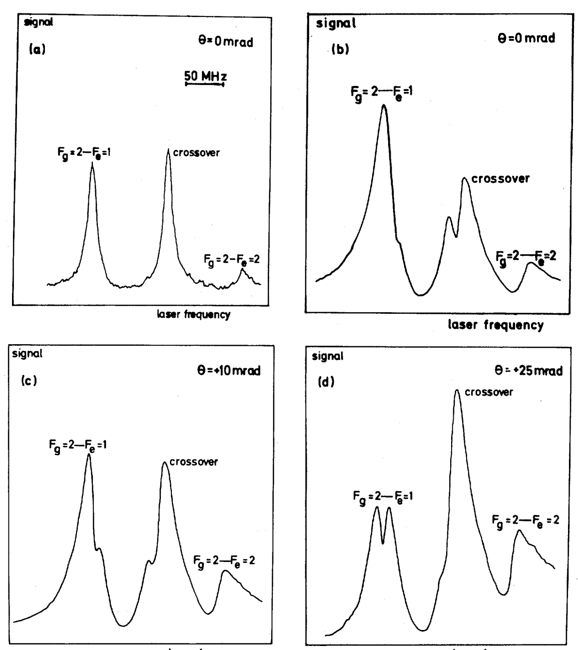

FIG. 3. Sections of polarization spectra in the Na D_1 line (transitions to $F_g = 2$): (a) weak probe beam, crossed polarizers ($I_p = 0.9$ mW/cm^2, $I_S = 5.6$ mW/cm^2); (b)–(d) spectra affected by the velocity-selective optical Hanle effect with strong probe and pump fields ($I_p = 23$ mW/cm^2, $I_S = 30$ mW/cm^2) and different rotations of the polarizers from their crossed position.

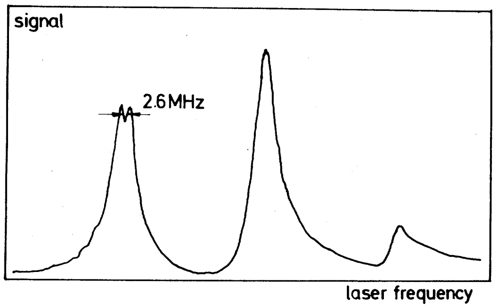

FIG. 4. An example of the narrowest subnatural dips obtained, with a width of 2.6 MHz. The crossing angle of the polarizers was $\theta=+12$ mrad; I_p and I_S were smaller than 10 mW/cm^2.

Figure 3(a) represents part of a typical polarization spectrum of the Na D_1 line, recorded with $\theta=0$, weak pump, and very weak probe beam ($I_S=5.6$ mW/cm^2, $I_p=0.9$ mW/cm^2). The 12-MHz linewidth of the resonances is composed of the natural width (10 MHz), the laser linewidth ($\simeq 1$ MHz), and a small contribution ($\simeq 1$ MHz) arising from the divergence of the light beams. If both beams are sufficiently strong ($I_p=23$ mW/cm^2, $I_S=30$ mW/cm^2) [Figs. 2(b) and 2(c)] a line asymmetry appears caused by two dispersive contributions of different signs and amplitudes for the ($F_g=2$)-($F_e=1$) and crossover resonances. By extending the model of Fig. 1 it can be shown that the signs of $\omega_L(\delta)$ and $s^r(\delta)$ are different for the direct resonance and the crossover. An appropriate angle $\theta\neq 0$ permits the observation of purely symmetrical signals [Fig. 3(d)] resulting from the velocity-selective optical Hanle effect. They appear as narrow dips in the power-broadened Doppler-free polarization spectroscopy signals. However, the conditions for production of dips as narrow as possible are competitive with the conditions for optimization of their amplitude: On the one hand the intensities I_p and I_S should be small to reduce power broadening of the dip; at the same time they have to be large enough to create the Zeeman coherence and to destroy it by the mechanism described before. Nevertheless, we have obtained signals as narrow as 2.6 MHz (26% of the natural width) with a size of about 10% of the total amplitude by reducing I_p and I_S below 10 mW/cm^2 (see Fig. 4). These dips not only have a smaller subnatural linewidth than achieved with other techniques,[3] but also exhibit a much better signal-to-noise ratio. Possible applications of this method to measurements of term energy differences are still under investigation.

In conclusion, we have demonstrated a new and rather simple method for obtaining optical resonances with subnatural linewidth. The technique is best suited for transitions where one of the levels involved is metastable but it should permit some line narrowing also when both states are short lived.

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