Modeling Polarization Reversal in Optically-Pumped Rubidium Vapor

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Introduction

Using the experimental setup shown in Fig. 1, we have studied the optical pumping of mixtures of Rb vapor and N_2 buffer gas. As the frequency of the right-hand circularly-polarized laser is varied across the D1 absorption profile, the electron spin polarization, P_e, of the Rb is found to take on negative values for small negative values of pump detuning from the absorption profile center (see Fig. 2).

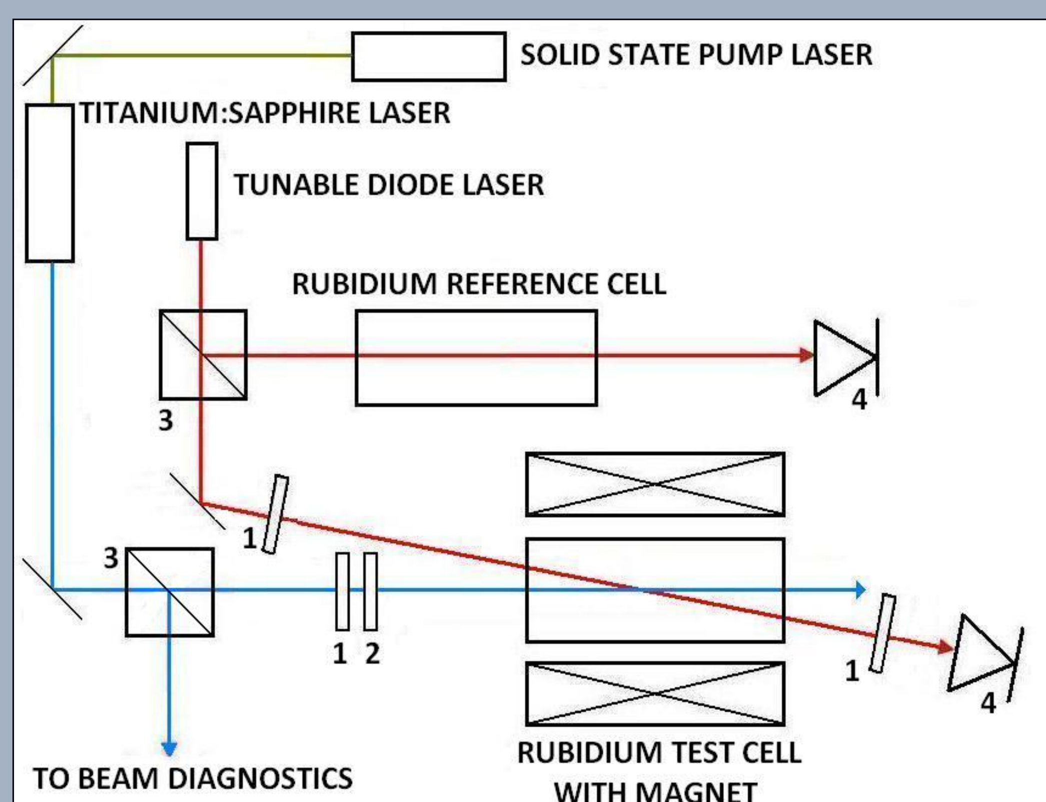

Fig. 1: Apparatus schematic: (1) linear polarizer; (2) quarter-wave plate; (3) beam sampler; (4) photodiode.

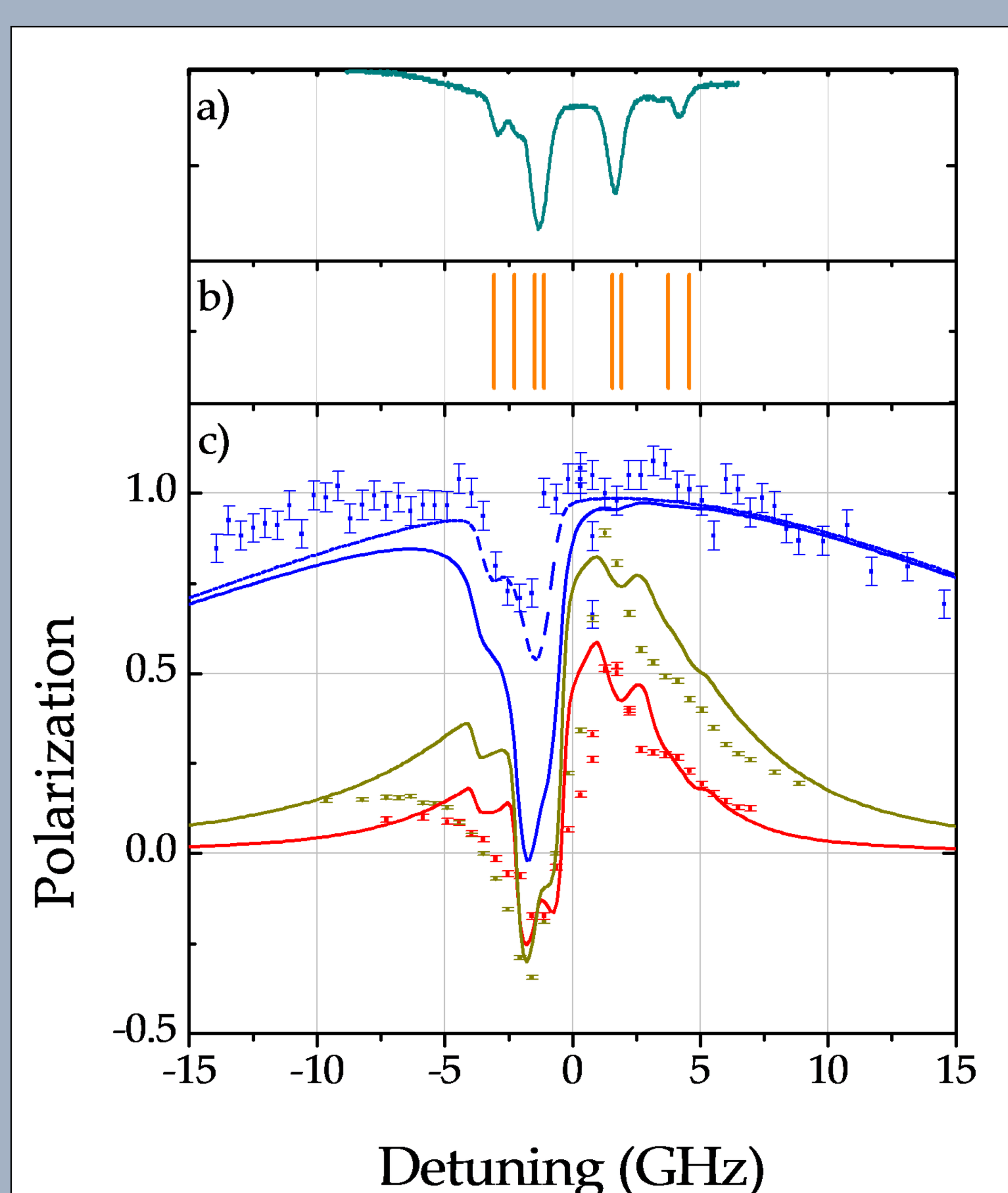

Fig. 2: a) Absorption scan of probe in Rb reference cell. b) Positions of hyperfine transitions, from left to right: ^{87}Rb $F_g = 2 \rightarrow F_e = 1$, ^{87}Rb $2 \rightarrow 2$, ^{85}Rb $3 \rightarrow 2$, ^{85}Rb $3 \rightarrow 3$, ^{85}Rb $2 \rightarrow 2$, ^{85}Rb $2 \rightarrow 3$, ^{87}Rb $1 \rightarrow 1$, ^{87}Rb $1 \rightarrow 2$. c) Measured and calculated polarization of Rb vapor as a function of pump laser frequency. **Blue data:** 10 Torr N_2, $4.3 \cdot 10^{12}$ cm^{-3} Rb; **solid curve:** 10 Torr N_2, 99.5% σ^+ light polarization; **dashed curve:** 10 Torr N_2, 99.95% σ^+ light polarization. **Green data:** 1.0 Torr N_2 and $8.8 \cdot 10^{12}$ cm^{-3} Rb; **curve:** 1.0 Torr N_2 and 99.5% σ^+ light polarization. **Red data:** 0.1 Torr N_2, $8.4 \cdot 10^{12}$ cm^{-3} Rb density; **curve:** 0.1 Torr, 99.5% σ^+ light polarization.

Spin Reversal

The spin reversal phenomenon is due to the underlying hyperfine structure of the optically-pumped Rb vapor. This can be understood by considering the Zeeman structure of ^{85}Rb (Fig. 3). When F < I + J, the expectation value of P_e for a given eigenstate of the hyperfine Hamiltonian is proportional to $-m_F$. Thus, for ^{85}Rb, if one could selectively populate the $^2S_{1/2}$ F = 2 state with $m_F > 0$, the polarization of the hyperfine-averaged J-states of the atom would exhibit $P_e < 0$. To achieve this by pumping the F = 3 → F = (2,3) transition, however, requires a non-σ^+ component of the pump laser polarization that can drive vertical or left-going absorptions in order to eliminate population of the F = 3, m_F = +3 dark state [1].

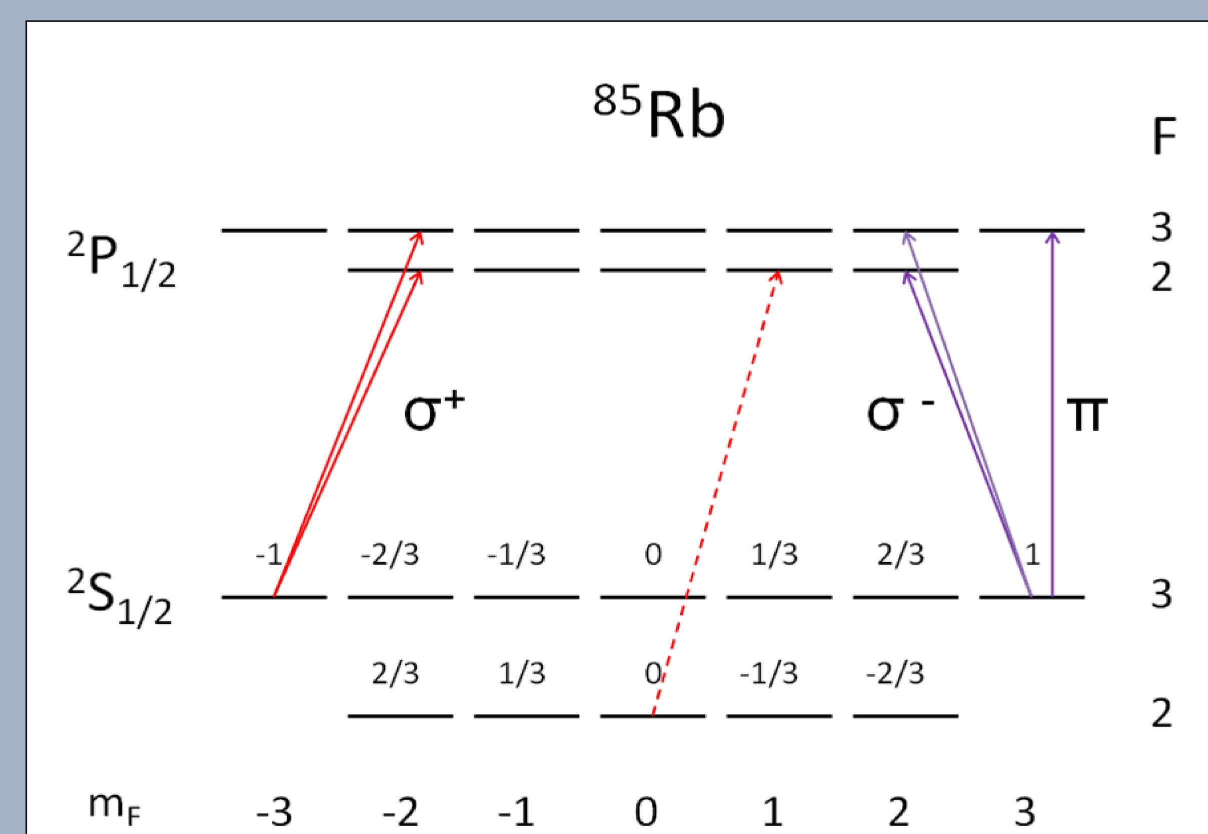

Fig. 3: Zeeman level diagram of ^{85}Rb. For ground m_F states, P_e is indicated above the level. With the pump beam along the cell axis, the indicated π transition can result only from poor pump laser collimation or misalignment. The σ^- transitions result from imperfect σ^+ polarization. The dashed arrow indicates repumping from the hyperfine ground state caused by pressure broadening.

Relevant Rates

There are four time scales of interest in this system associated with:

- The optical pumping rate determined by the optical absorption cross section and the pump laser intensity.
- The depletion of the F = 3, m_F = +3 state dependent on the intensity of non-σ^+ polarization.
- The spin relaxation rate decreasing with buffer gas pressure.
- The repump rate from the F = 2 state, increases with buffer gas pressure.

The optical pumping rate is much greater than the others; it exceeds the spin relaxation rate with our buffer gas pressures and, like the dark state depletion and repump rates, it depends on the pump laser intensity but has a much higher constant of proportionality.

Model

We have modeled these effects with rate equations for the individual F, m_F ground- and excited-state sublevels for ^{85}Rb and ^{87}Rb assuming:

- The laser beam is spatially flat in both radius and distance along the cell axis, having an adjustable superposition of σ^+ and σ^- light.
- The optical absorption is described by a Voigt profile convolution of the Doppler-broadened Gaussian line shape with the natural width [2] and collisional Lorentzian line shape.
- The laser-induced pump-, dark-state depletion-, and repump-rates are obtained by integrating the overlap of the laser spectral profile with the absorption line shape for the relevant transitions.
- The spin relaxation rate is the diffusion rate for atoms to cross the laser beam with N_2 gas, joined smoothly to the beam-crossing rate for atoms in vacuum when the diffusion length matches the beam diameter.

The intensity, diameter, and σ-polarized fraction of the light are the only free parameters in the calculations. Rate equations for ^{87}Rb and ^{85}Rb are solved independently, and their results combined in a weighted average for the sample.

Results

The predictions of the model are depicted as the solid-line curves in Fig. 2c with the fit parameters of laser power = 100 mW, the laser radius = 0.5 mm, and the fraction of σ^- polarized light = 0.005. The model gives reasonable agreement with the data. The dashed-line curve shows the results for 10 Torr with the fraction of σ^- polarized light = 0.0005. As the data sets were taken on different days, the waveplate may have been set slightly differently for the 10 Torr data set or experienced a small rotation around the vertical axis, which would yield different polarizations at the respective optimal settings.

Acknowledgments

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References:

[1] Mike Romalis (Princeton University) made us aware of the importance of a non-σ^+ fraction in the pump beam for the production of $P_e < 0$.
[2] D. A. Steck. “Rubidium 87 D Line Data”. (2003). Available online at < http://steck.us/alkalidata/>.