Laboratory Experiment for Polarized Scattering at Potassium Vapor

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Abstract. The observed solar polarization peaks of the D1 lines of sodium at 5896 Å and barium at 4934 Å still elude theoretical explanation, in spite of considerable theoretical efforts over the past decade. To clarify the underlying physics of D1 scattering we have set up a laboratory experiment to explore the spectrally resolved profiles of the Mueller matrix for D1 and D2 scattering at potassium vapor. Here we present initial results of this experiment.

1. Introduction

The pronounced and symmetric polarization signatures that have been repeatedly observed in the Doppler cores of the Ba II D1 line at 4934 Å and the Na I D1 line at 5896 Å (Stenflo & Keller 1996; Stenflo, Gandorfer, & Keller 2000a; Stenflo, Keller, & Gandorfer 2000b) appear to contradict predictions from quantum mechanics, and have remained enigmatic for many years, in spite of numerous theoretical attempts to explain the observations (cf. Landi Degl’Innocenti 1998, 1999; Trujillo Bueno et al. 2002; Kerkeni & Bommier 2002; Casini et al. 2002; Klement & Stenflo 2003; Casini & Manso Sainz 2005). The theory fails by 1–2 orders of magnitude in the polarization and predicts the wrong symmetry for the core profile. To answer the question whether this problem is one of solar physics or one of quantum/atomic physics, we have set up a laboratory experiment to study the properties of polarized scattering in the potassium transitions K I D2 7664.9 and K I D1 7699.0 Å. These transitions have the same quantum structure as the Ba II and Na I lines, including hyperfine structure splitting, and have the decisive advantage that a solid state tunable laser can be used as a light source in this spectral range. The setup consists of the laser, polarizing beam splitter, potassium vapor cell, polarization analyzer based on piezoelectric modulation, transfer lenses, and photomultiplier with lock-in amplifier. As the laser allows monochromatic excitation of the potassium atoms, the experiment gives us the polarization for 90° scattering as a function of position within the line profile.

2. Experiment Setup

The present setup represents a successful second-generation version of our D1 scattering experiment. In the first and unsuccessful generation of this experiment
we attempted to mimic solar conditions by irradiating sodium gas with either polarized or unpolarized radiation from a moderately broad-band light source (a low-pressure sodium lamp), while separating the D$_1$ and D$_2$ lines with a narrow-band filter. This experiment failed for a number of reasons: insufficiently clean separation of D$_1$ and D$_2$, insufficient S/N ratio, and inacceptably high stray-light levels. In addition no information on the profile shape was obtained. We then realized that there is absolutely no reason to try to reproduce the Sun, since what we are after is to test the underlying quantum-mechanical scattering theory under the most optimum conditions that best constrain this theory, and the best setup for doing this has little if any resemblance to solar conditions.

All the problems of the previous experiment are completely eliminated if a tunable laser is used. It not only provides fully resolved polarized line profiles with superb S/N ratio and no spurious contaminations, but also brings other information, like on the optical pumping properties. Since solid-state tunable lasers are not available for the sodium wavelengths, we choose to do our experiment with potassium gas instead.

We thus irradiate a sample of potassium gas with a tunable narrow-band laser and measure the polarization of the light scattered at 90°. By tuning the laser wavelength across the spectral line, we can fully resolve the line profile without having to use a spectrograph (which would not have worked because the S/N ratio would have been reduced by orders of magnitude). Figure 1 provides a schematic overview of the laboratory setup.

The heart of the experiment is a cross-shaped glass cell containing potassium vapor, built for this purpose by A. Cacciani in Rome. Cells based on the Cacciani design have been used for decades in solar astronomy (cf. Cacciani & Fofi 1978; Cacciani 1987; Cacciani, Moretti, & Rodgers 1997). Argon buffer gas in the cell prevents the potassium from condensing onto the entry and exit windows. We use a vapor temperature of 100° C.

The source is a 15 mW solid-state laser, tunable across 2.5 Å, of which we use about 200 mA. The spectral width is less than 2 mA. We expand the beam and pass it through a set of polarizers, pumping the K vapor with a selection of six Stokes states: 100% $\pm Q/I, \pm U/I, \pm V/I$. We use two dedicated lasers, centered around the D$_1$ and D$_2$ lines, respectively.
Figure 2. Stokes $Q \rightarrow Q$ measurements and Mueller matrix elements for the 
$K \rightarrow D_1$ line. The solid and dashed profiles represent measurements with 
the full laser power, the dotted lines with only a tenth of the full power. For the 
dashed profiles an artificial instrumental polarization was introduced by tilting 
an optical component. **Top:** total intensity profile, i.e., $P_{11}$. **Center:** Stokes-$Q$ 
profiles for input states $100\% +Q/I$ and $-Q/I$, respectively. **Bottom:** phase 
matrix elements $P_{21}$ and $P_{22}$ as calculated from these two measurements. 
Note how the artificial instrumental polarization vanishes for $P_{22}$ (but not for 
$P_{21}$), as expected.

In a second optical arm, light scattered at $90^\circ$ passes through a photo-
elastic modulator and a polarizer, which convert the polarization information 
of one Stokes component ($Q$, $U$, or $V$) into an intensity modulation (at 84 kHz for 
$Q$ and $U$, at 42 kHz for $V$). A photomultiplier detects the signal, and a lock-in 
amplifier demodulates it. Combined with the 6 input polarization states and 
the 3 output states, a full measurement set consists of 18 line profiles.

3. Data Acquisition and Reduction

3.1. Procedure to Obtain the Empirical Mueller Matrix

For each of the $6 \times 3$ combinations of input and output polarization states, we 
tune the laser through the spectral line and correct the recordings for dark cur-
rent and calibration. Since absolute intensity cannot be measured reliably with 
our setup, we normalize all (wavelength-dependent) Stokes vectors by the max-
imum of the intensity curve. Furthermore, we subtract a constant polarization 
offset from each polarized flux curve to set the polarization level outside the line 
profile to zero, since $Q$, $U$, $V$ must go to zero outside the line as $I$ goes to zero 
there.

From this set of polarization profiles, the elements of the phase matrix 
$P_{ij} \ (i,j = 1, \ldots, 4)$ can be extracted (renormalized to the maximum of $P_{11}$). 
Figure 2 shows how the matrix elements of rows 2, 3, and 4 are determined as
Figure 3. Phase matrix elements for the K i D1 line. In each frame, the solid curves come from measurements with input 100% $\pm Q/I$, the dotted ones from 100% $\pm U/I$, and the dashed ones from 100% $\pm V/I$. In the right panels these three types of curves represent $P_{i1}$, $P_{i3}$, and $P_{i4}$, respectively ($i = 2, 3, 4$).

illustrated for the example of the $Q \rightarrow Q$ measurements. The element $P_{11}$ simply describes the shape of the total intensity profile. Since the input Stokes vectors have the shape $I(1, \pm 1, 0, 0)^T$ (where T indicates the transpose operation), the measured $Q$ profiles represent $P_{12} \pm P_{22}$, respectively. Thus, $P_{12}$ is simply half the sum, and $P_{22}$ half the difference, of the two $\pm Q \rightarrow Q$ measurements. By applying this method to all 18 combinations of input and output polarizations, we get 18 independent measurements of $P_{11}$, 3 for each $P_{ij}$, and one for each of $P_{2j}$, $P_{3j}$, $P_{4j}$, where $j = 2, 3, 4$.

Note that since $P_{2j}$, $P_{3j}$, $P_{4j}$ are formed as the difference between two measurements, instrumental polarization effects subtract out completely. This is not the case for $P_{1j}$, since it is formed as the sum of two measurements (see Fig. 2).

3.2. Test Measurements

When the laser power is reduced, the results remain the same, except in the case of $+V \rightarrow V$, for which the signal is diminished. This non-linearity indicates that optical pumping and atomic polarization are involved. Reducing the temperature of the K gas simply reduces the scattered intensity but not the amount of polarization.

For another series of $Q \rightarrow Q$ measurements, an artificial instrumental polarization was introduced by tilting an optical component. This produced an $I \rightarrow Q$ cross-talk, but left matrix columns 2–4 untouched, since for them the offset subtracts out (see previous section). $P_{1j}$ may therefore contain spurious fractions of the $P_{11}$ profile, while $P_{2j}$, $i, j = 2, 3, 4$, are robust and free from such effects.
Finally, an experiment was conducted with the PEM placed before rather than after the scattering cell, i.e., the gas was pumped with polarization modulated at 84 kHz. In this case, the $Q \rightarrow +Q$ profile exhibited a strong intensity dependence: For full laser power, a negative peak of $Q = -0.08\%$ was observed. For $1/2$ and $1/5$ power, the $Q$ polarization was greatly reduced. For $1/10$ of the full laser power, the signal vanished completely. This behavior can be understood if the optical pumping takes place on a time scale that is comparable to the modulation period, i.e., $\sim 10^{-5}$ s.

4. Results

Figures 3 and 4 show all the reconstructed phase matrix elements for the K $\rightarrow$ D$_2$ lines, respectively. The lasers were run at full power, instrumental artefacts were minimized as far as possible, and no magnetic field beyond the Earth’s field was applied. The noise level is of order $2 \times 10^{-5}$. A very conservative wavelet smoothing algorithm has been applied to the polarized profiles. Remember that the polarized matrix elements of the first column of the Mueller matrix (left panels in the figures) are likely to include some cross-talk from the $P_{11}$ profile, while those in the right panels do not.

Note how the independent measurements of $P_{11}$ and $P_{21}$ match each other perfectly, which confirms the consistency and repeatability of the measurements. In the case of $P_{31}$ and $P_{41}$, it is mainly the curves with circular input polarization that deviate from the other two, apparently due to non-linear optical pumping effects.

Since the D$_2$ line is better understood than D$_1$, it can be used to estimate the collision depolarization factor for both experiments, i.e., the factor by which the polarizations should be scaled to represent the collision-free case. We estimate it to be $\sim 34$. Such a large value is almost unavoidable when using a buffer.
gas to avoid potassium deposits on the cell windows. However, since it may be regarded as a global scaling factor for both $D_1$ and $D_2$, and since our measuring system provides a very high S/N ratio even with the low polarization levels that we are dealing with, collisional depolarization is not a critical issue here.

5. Conclusion and Outlook

To shed light on the complex physics that underlies the enigmatic solar barium, sodium, and potassium $D_1$ polarization we have set up a laboratory experiment to explore the basic scattering physics under highly idealized and controlled conditions. The experiment is giving us a rich set of fully resolved polarized profiles with high S/N ratio for the scattering Mueller matrix elements. This empirical dataset will provide powerful constraints on the underlying theory of quantum scattering and guide the theoretical efforts that we are currently undertaking.

In a second phase we are investigating the behavior of these matrix elements under the influence of external magnetic fields. We have Helmholtz coils capable of delivering any field strength within $\pm 40 \text{G}$, which we can mount around the arms of the vapor cell along any of the three coordinate axes. The observed fact that the unexplained sodium $D_1$ polarization is found to vary substantially with location on the Sun (cf. also the potassium $D_1$ measurements presented in these proceedings by Stenflo (2006)) suggests that the solution of the solar enigma has to involve magnetic fields. After the Boulder Workshop, measurements with a magnetic field perpendicular to the scattering plane have been conducted for $K \lambda D_1$ with spectacular and quite unexpected results.

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References

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