OPTICAL SPECTROSCOPY AND THE ZEEMAN EFFECT

Beyond the First Year workshop
Philadelphia, July 25-27 2012
Greg Elliott, University of Puget Sound

The Zeeman effect offers a striking visual demonstration of a quantum system and provides a detailed, multi-faceted corroboration with the theoretical treatment. How can one see the effect and observe the various experimental dependences and not end up believing in quantum mechanics? At the University of Puget Sound the effect is first introduced at the sophomore level in Modern Physics, and then treated in full mathematical detail in senior level Quantum Mechanics. The seniors spend some time observing and quantifying the effect, as one of a few experiments that complement their theoretical studies. Students have also explored the effect in the advanced lab course, and as independent study and summer research projects.

Following an NSF sponsored workshop on advanced lab curricula in the 1990's, we built an Ebert spectrometer to observe and study the Zeeman effect and the fine structure of hydrogen.[1] Our instrument has evolved over the years, and now consists of four elements: (1) a discharge source in the field of either a permanent magnet or an electromagnet, which illuminates an adjustable width slit, (2) an objective mirror (12" diameter f/8), (3) an Echelle grating on a rotary stage, and (4) a ccd camera detector. Working at high order (~20-25), the Echelle grating can give a resolving power in excess of 500,000 and a resolution of about .001 nm in the visible.

A mercury discharge produces several transitions of interest for observing the Zeeman effect.[2] The normal effect is observed for the yellow ${}^1D_2 \rightarrow {}^1P_1$ transition at 579.065 nm yielding three lines. The anomalous effect is observed for the blue ${}^3S_1 \rightarrow {}^3P_1$ at 435.835 nm (six lines) for the yellow ${}^3D_2 \rightarrow {}^1P_1$ transition at 576.959 nm (nine lines) and the green ${}^3S_1 \rightarrow {}^3P_2$ transition at 546.074 nm (nine lines). The splittings and the line polarizations yield a quantitative test of the agreement with the predictions given by the Lande g-factor.

In this workshop I will give a brief tour of the instrument, discuss some of the experimental difficulties in its construction and operation, and demonstrate the effect for the mercury (and other) systems. The following material gives background on the apparatus and its components and on the mercury system.

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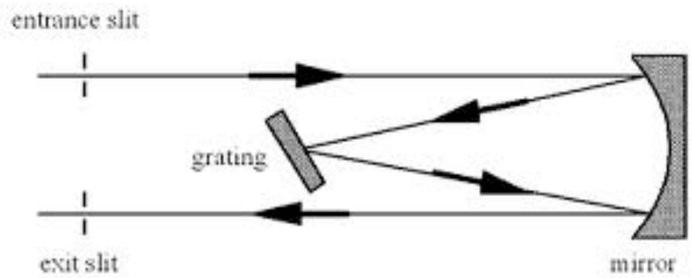
[1] D. Preston and E. Dietz, *The Art of Experimental Physics*, Wiley 1991.
[2] G. Herzberg, *Atomic Spectra and Atomic Structure*, Dover, 1944.

EBERT SPECTROMETER

The Ebert configuration is carefully described in Preston and Dietz, and is shown schematically below. Light from the entrance slit is collimated, then diffracted, and then a specific wavelength component is focused onto the exit slit.



Our objective mirror is 12" in diameter and approximately f/8 (an old telescope mirror). A long focal length produces a large linear dispersion at the exit slit, and a large diameter allows the mirror to serve double duty in the two-pass configuration. The entrance slit is located at the focal distance from the mirror and light from it fills a good fraction of the mirror (being partly blocked by the grating). The mirror reflects collimated light to the grating. The light diffracted from the grating is likewise collimated. Rotating the grating allows alignment of a diffracted beam of a specific wavelength to be incident back on the objective mirror and focused onto the exit slit. The ray diagram is somewhat misleading: the light beams incident and diffracted from the grating are very nearly parallel, and the slits send light to or collect light from the whole surface of the objective mirror. For our setup, we use a diverting mirror near the grating to send the output beam to a ccd camera (instead of an exit slit), to physically separate the source and magnet assembly from the camera assembly.

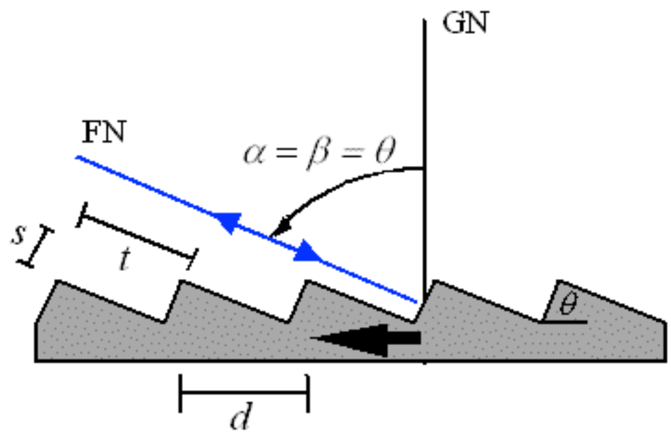
ECHELLE GRATING

To theoretical limit for the resolving power of a grating depends both on the total number of ruled lines on the grating, N, and the order of the diffracted beam, m:

$$\frac{\lambda}{\Delta\lambda} = mN$$

For many years we worked in second or third order from a finely ruled grating with a resolving power in the range of 250,000 - 400,000. This gave adequate results for observing and quantifying the Zeeman effect, but was inadequate for resolving the fine structure of hydrogen. A few years ago we acquired an Echelle grating (from Richardson Gratings), which is ruled with fewer lines/mm, and can therefore work in much higher order. Our grating has 150 lines/mm and is 200 mm wide, so N = 3000, but we can now work at orders above 20. In addition, the blaze of the grating is optimized for high angles, and gives more intensity at high angles than our finely ruled grating.

An Echelle grating works well in the Littrow configuration, where the diffracted beam (angle -β from the grating normal, GN) comes out along the incident beam (angle α), both oriented close to the direction of the face normal (FN, angle θ).



In the Littrow configuration β = -α, and the diffraction condition

$$\frac{2\pi}{\lambda}\sin\alpha = \frac{2\pi}{\lambda}\sin\beta + \frac{2\pi}{d}m$$

becomes

$$2d\sin\alpha = m\lambda$$

ZEEMAN EFFECT

The spectral line splittings of electronic transitions for atoms in a magnetic field can be easily observed with a spectrometer working with sufficient resolving power (typically in excess of 250,000). The theoretical treatment is beautiful and a good workout in perturbation theory for senior undergraduates (see Griffiths, for example). In the weak magnetic field regime, the Lande g-factor determines the relative size of the energy shift of an electronic level characterized by quantum numbers *S, L*, and *J*:

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

and

$$\Delta E = \mu_B g B m_J$$

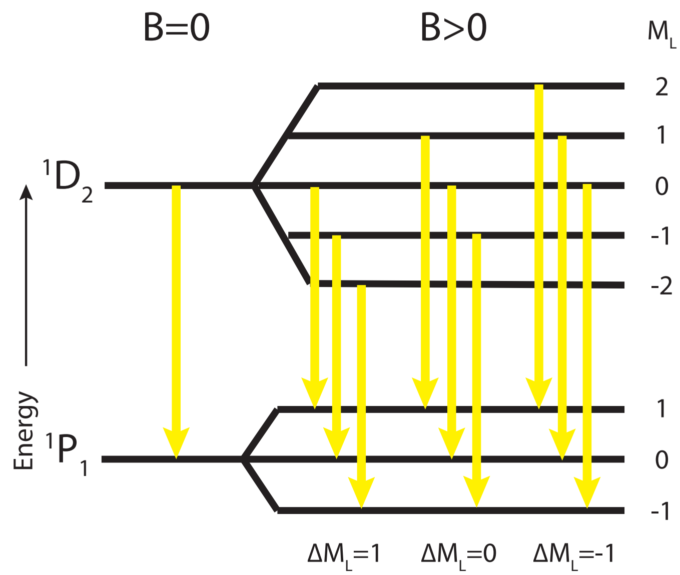
where μ_B is the Bohr magneton, B is the magnetic field strength, and m_J is the projection of the total electronic angular momentum along the field direction.

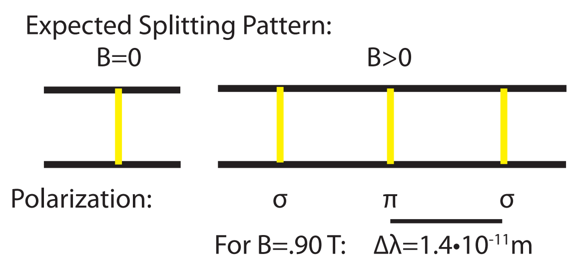
As a refresher for those of you like me, the notation for the electronic configuration of a level with angular momenta *S, L*, and *J* is given as

$$^{2S+1}L_J$$

where $2S+1$ and *J* are expressed numerically and *L* is expressed as *S, P, D, F*, ... for 0, 1, 2, 3,.... For example, the transitions for Hg shown on the following page are between the levels $^1D_2$ and $^1P_1$. Both are singlets (S = 0); J = L both change from 2 to 1. The Lande g factor is 1, so this transition exhibits the normal Zeeman effect. The mercury blue transition occurs between $^3S_1$ and $^3P_1$ levels. S = 1 and J = 1 for both; L changes from 0 to 1. The Lande g-factor and therefore the splittings are different for the two levels, and this transition exhibits the anomalous Zeeman effect. The polarization of the light from a transition depends on the change in the projection of the orbital angular momentum along the field direction, with $\Delta m_l = 0$ producing π polarization and $\Delta m_l = \pm 1$ producing σ polarization. Two other Mercury transitions are also shown on the following pages, along with images from the spectrometer showing the Zeeman splittings and their polarization dependence. In our workshop we should be able to observe each of these four cases.

Mercury yellow line at 579.065 nm
Normal effect for the $^1D_2 \rightarrow {}^1P_1$ transition (three lines)



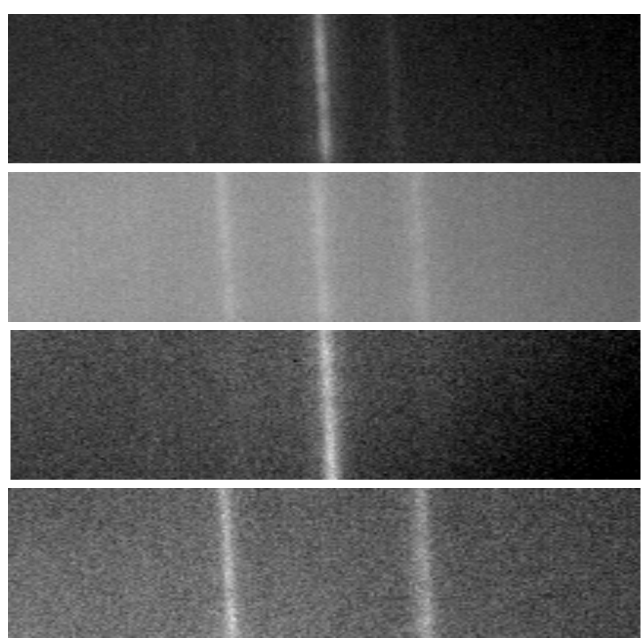


no B field

no polarizer

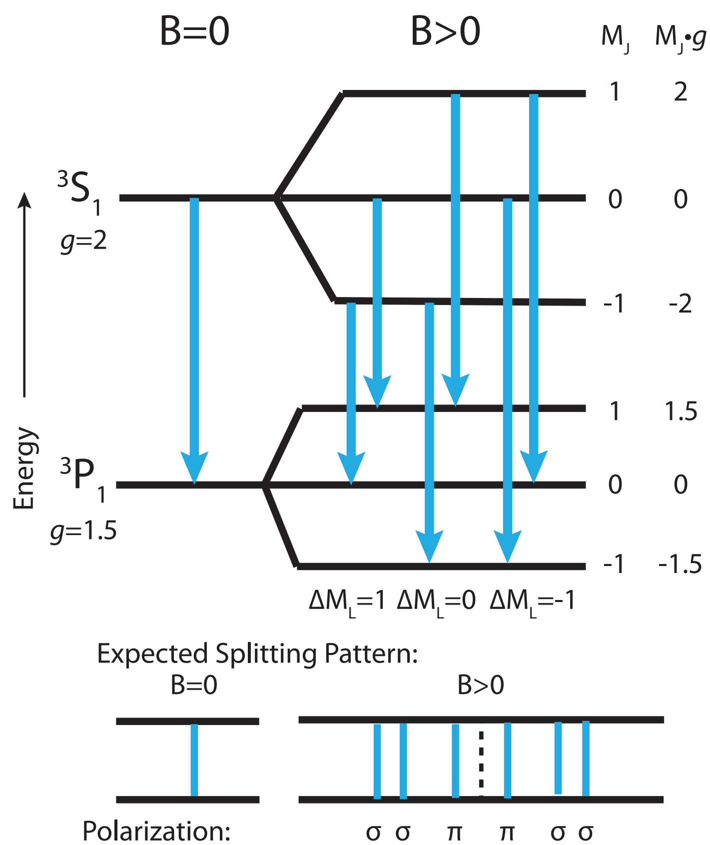
π polarizer

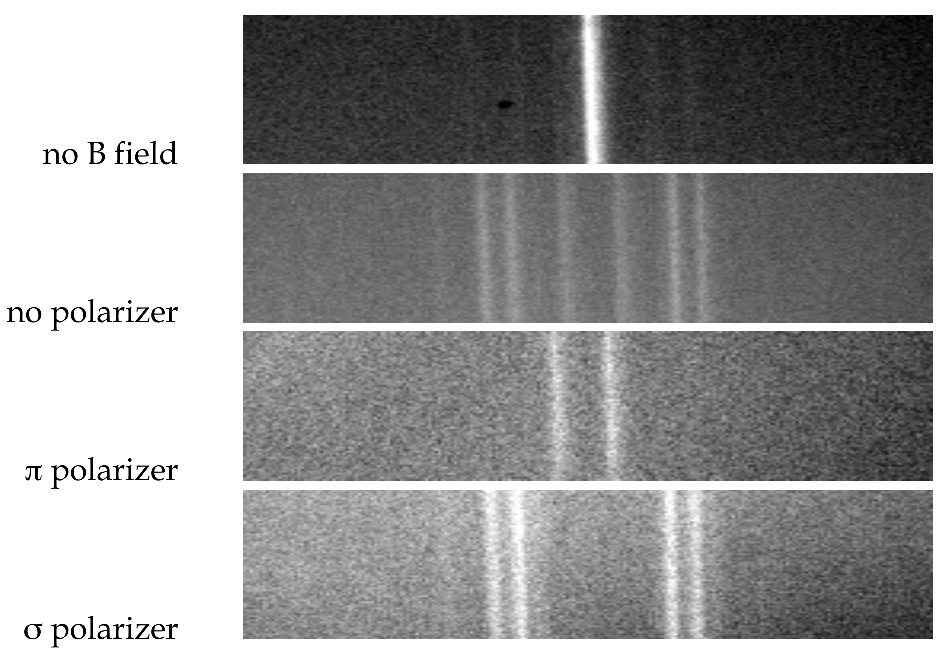
σ polarizer



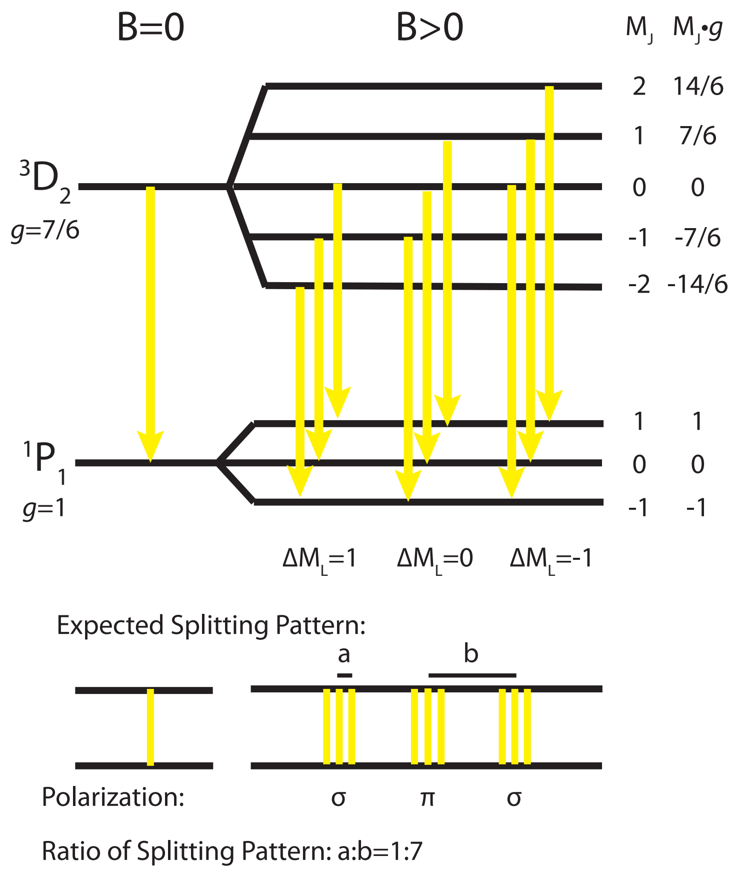
Mercury Blue line at 435.835 nm

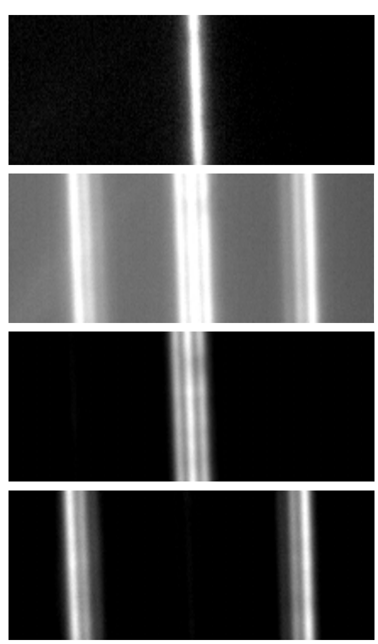
Anomalous effect for the $^3S_1 \rightarrow {}^3P_1$ transition (six lines)





Mercury yellow line at 576.959 nm
Anomalous effect for the $^3D_2 \rightarrow {}^1P_1$ transition (nine lines)





no B field

no polarizer

π polarizer

σ polarizer

Mercury green line at 546.074 nm
Anomalous effect for the $^3S_1 \rightarrow {}^3P_2$ transition (nine lines)