The Zeeman Effect
or
How to measure the magnetic field of a star

Overview

The energy levels in an atom are sensitive to the magnetic field in which the atom is placed. This phenomenon is known as the Zeeman effect. It is widely used in astronomy to estimate the magnetic field in the outer regions of stars. It is also an important part of the study of the energy level structure of atoms. A Fabry-Perot étalon is used in a constant deviation spectrometer to study the splitting of atomic energy levels in Neon in an applied magnetic field. **The charge to mass ratio for an electron is obtained from the splitting of the energy levels**.
Polarization of light emitted by the de-excitation of specific levels is also studied.

This is a two-week experiment.

Risk assessment

You should consider and note in your laboratory notebook any risks to yourself or to the apparatus as you prepare to start the experiment. You are advised to read through the whole script before you start to use the apparatus. You should consult a demonstrator as indicated in this script and if you need help.

Physics

Some of the physics of this experiment will be new to you. The apparatus used is a Fabry-Perot étalon, in conjunction with a constant deviation prism spectrometer. The techniques involved in this experiment allow you to measure changes at optical wavelengths of $\delta\lambda/\lambda \sim 10^{-5}$. These correspond to energy changes in the atomic levels of $\sim 10^{-5}$ eV.

Light from the spectral lamp develops structure (also known as 'splitting') when the lamp itself is placed into a magnetic field. Measurement of the magnetic field requires the use of a Hall probe. Quantum mechanical effects are important in understanding the underlying physics. The spin, orbital and total angular momentum of the atomic state determine how the atomic transition responds to the applied field. In particular, the importance of the magnetic quantum number '***m***' is shown through the splitting of an atomic energy level with non-zero angular momentum. This is a very brief introduction to the Zeeman effect. You are not required to understand the theory of how the Zeeman effect works in any detail.

Consideration of the polarization and angle of emission of the photons with respect to the magnetic field illustrates some properties of the electron wave functions in the excited atom. To obtain the polarization measurements an understanding of linear and circular polarization of light and the methods of detecting these polarizations is required.

Apparatus

The apparatus is shown schematically in Figure 1. There are three basic components. There is a light source which is a neon-discharge lamp positioned between the poles of magnet. There is a prism spectrometer and there is a Fabry-Perot étalon. For the last part of this experiment only, a polaroid filter and quarter wave plate, which are used to determine the polarization of the light, will need to be positioned between the lamp and the spectrometer.

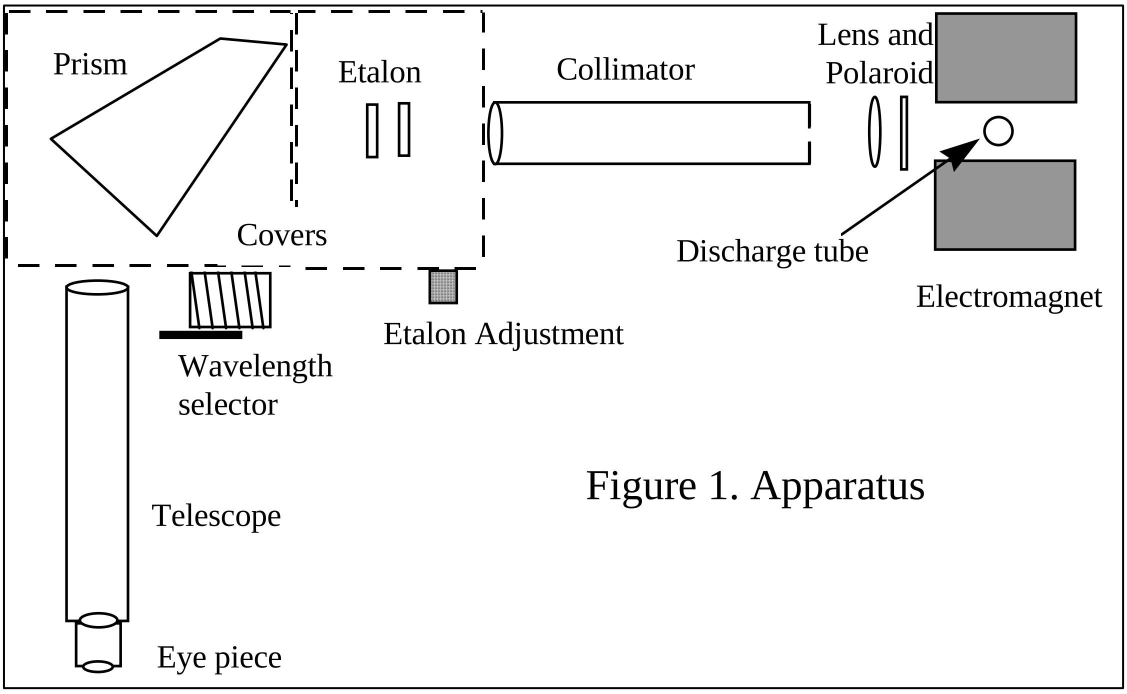

Figure 1. Apparatus

The neon-discharge lamp is powered by a fixed high-voltage supply. The magnetic field is provided by an electromagnet of variable field strength The whole magnet assembly can be rotated so that the light emitted by the lamp can be viewed either parallel to or normal to the applied magnetic field. You will find that the structure visible in the spectrum of the light from the lamp will depend on the orientation of the magnetic field. Initially the alignment should be such that the light emitted is viewed perpendicular to the applied field. The pole pieces have a hole through the centre and this will later allow the light to be viewed in the field-parallel arrangement.

There is a high-current DC power supply to energise the coils of the electromagnet.

IT IS VERY IMPORTANT THAT THE MAGNETIC FIELD BE INCREASED AND DECREASED SLOWLY!

Always reduce the current through the coils to zero before switching off (or on) the DC supply. Particular care should be taken when the field is to be removed. You should consult the demonstrator before operating this power supply.

- *Ensure that you understand the configuration of Helmholtz coils that provide the magnetic field and why the field should be changed slowly.*

The spectrum of the light from the lamp can be analysed using the combination of the prism spectrometer and the étalon. Consider the operation of this apparatus without the étalon in place initially. We will come back to the action of the étalon later. The first lens outside the spectrometer acts to illuminate the entry slit with light from the neon lamp. The collimator is shown as a tube with a slit at one end and a lens at the other. The slit is placed in the focal plane of the lens so that the lens will produce quasi-parallel light from it. The width of the slit can be adjusted with a micrometer.

- *The slit can be adjusted both in height and width and there is also a stop (or block) that cuts out the light altogether. If you fail to see any light at the telescope check that the stop has not been closed.*

The light then passes into the prism inside the angled cover plate. The prism is made of a glass whose refractive index depends strongly on the wavelength of the incident radiation. Hence it produces dispersion (or splitting of the light into component colours) when the light is refracted. The shape of the prism is such that it acts to produce a deviation in the horizontal plane of about 90º dependent on the wavelength of the light. The input collimator and the output telescope are aligned at 90º to each other. Thus, as the prism is rotated using the wavelength selector knob, a different wavelength will be directed down the second tube and can be viewed with the eyepiece. This is why it is called a 'constant deviation' spectrometer. In practice, a small range of wavelengths is seen. A slit-width control and pointer are incorporated into the eyepiece housing.

A lens to focus the light onto the entrance aperture may need to be placed between the lamp and the spectrometer. The lens will increase the illumination level, but you may prefer to work with lower light levels and less scattered light. You should experiment to see what you prefer.

You should use the prism spectrometer to notice that the neon lamp contains many spectral lines. We will be interested in those in the red/yellow region of the spectrum. The method for aligning the spectrometer is given below.

- *Ensure that you understand the action of all the optical components of the spectrometer. Your laboratory notebook should contain enough information to convince the marker that you understand how the spectrometer works.*

You need enough wavelength resolution to allow the effect of the magnetic field on the spectral line to be analysed. The prism on its own is not capable of this and so a higher resolution component is required. The details of how the étalon works are given elsewhere in the script. It is sufficient for here to say that it produces a circular fringe pattern with bright rings at different radii. Each independent wavelength produces an independent pattern. Figure 2a below illustrates the fringe pattern seen with the étalon.

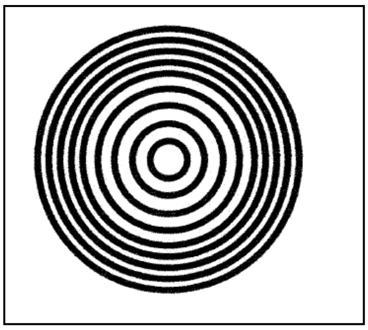

Figure 2a: Fringe pattern produced by an étalon illuminated by monochromatic light and an extended source. Note that as the observations are made in the back focal plane of a lens they are essentially intensity as a function of off-axis angle through the étalon.

The device is capable of separating components that are very close in wavelength. However, there is a problem with the étalon in that it does not cope well with a wide spectral range. Although the rings from wavelengths that are very close to each other will be separated, those from very different wavelengths may well overlap. The phenomenon is similar to overlapping orders in the diffraction from a grating - only more extreme. It is not uncommon for high resolution devices to suffer from this defect.
The solution to the problem is to use the combination of a low-resolution prism spectrometer and a high resolution étalon. This is the configuration used in this experiment. We will see that the prism produces low resolution in the horizontal direction and the étalon produces high resolution in the vertical direction.

The étalon is kinematically located on a 3-point support. However, you will need to adjust the orientation of the étalon. Under the cover next to the collimator is the adjustable support for the étalon housing. (You should remove both of the covers to see the étalon and the prism. Replace the covers before you start to focus the spectrometer and take readings. Do not touch the surfaces of the optical components.) The angle of tilt of the étalon can be adjusted by means of the screw controls at the side and below the etalon housing. Do not adjust any screw controls on the étalon itself!

- *Ensure that you understand the action of the étalon in the spectrometer. Why is the étalon placed in a section that has quasi-parallel light?*

Method

At this point you should have completed your risk assessment for everything but the Hall probe that you will use to measure the magnetic field strength.

Initially, you should remove the étalon from the spectrometer. With the magnet positioned so that the light emitted at right angles to the field is viewed by the spectrometer, use the lens to focus the image of the lamp onto the entrance slit of the collimator. Ensure that the lamp image falls on the entrance slit and that the slit is not fully closed, then view the spectrum of lines through the telescope.

Telescope adjustment.

Once you have seen a line spectrum in the telescope, set up the spectrometer by first viewing the small pointer at the eyepiece. Adjust the eyepiece, by sliding it, with a gentle twisting action, back and forth in its housing, until the pointer is in focus. Next look at the line spectrum and adjust the telescope focus (knob half way down the telescope) until you see a well-focused image[1]. The neon spectrum contains many lines. You will be working with one that shows a simple Zeeman effect. The wavelength of the line to be used is 585.2nm and its colour is yellow.

- *Consult the demonstrator to ensure that you have correctly identified the required line.*

Use the wavelength selector to position the yellow line on which you will make your measurements in the centre of the field of view. Adjust the width entrance slit of the collimator so that lines of different colour do not overlap. The action of the entrance

[1] Working in pairs you may disagree about the adjustment of the telescope. If this is the case one person should set it up and take a set of readings with the other person taking notes etc. Then reverse roles.

slit is essentially to define the range of angles that can pass through the spectrometer. Now place the étalon on to its supports. You should see that the line spectrum is fragmented. (Figure 2b). This is because the étalon produces a set of circular fringes for each wavelength of light incident on it. These are superimposed on the existing line spectrum. The centre of the circular fringe pattern now has to be positioned centrally above or below the field of view (use the étalon tilt controls at the side of and below the étalon cover). This is for ease of measurement.

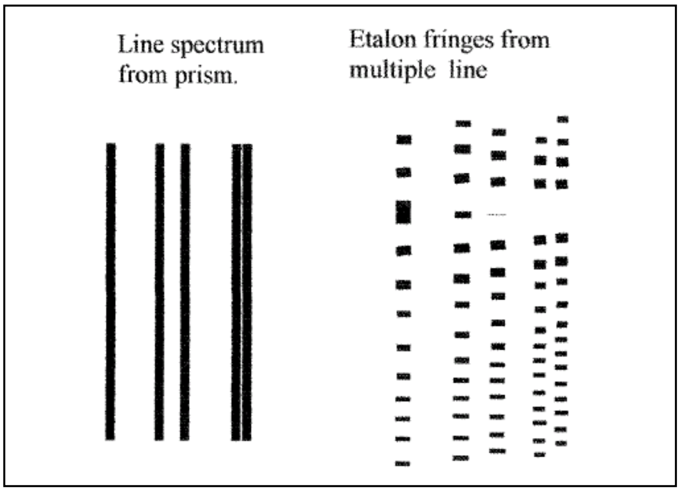

Figure 2b
Spectral lines with and without the étalon in the spectrometer

Now turn on the magnet power supply and increase the magnetic field while viewing the spectrum in the telescope. Each single horizontal yellow line should split into three. The magnetic field strength should be measured (see section below for instructions) when the upper and lower branch from an adjacent pair of lines merge, as shown in figure 3.

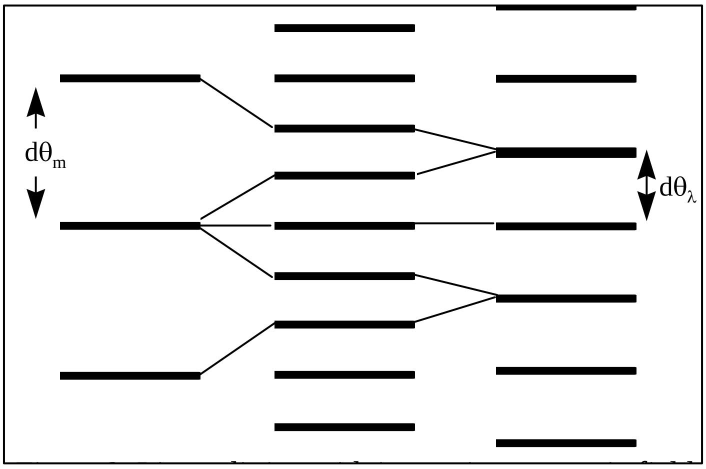

Figure 3
Line splitting observed at three different values of the applied magnetic field.

From the left, the figure shows the pattern with no field, low field and sufficient field to cause the split lines to overlap. The two angles indicated on the figure are $d\theta_m$ which is the angular difference in the position of two bright rings with no applied magnetic field, and $d\theta_\lambda$ which is the separation between the rings when the field is sufficient to cause overlap. The importance of these will become clearer in the optics theory section.

Measurement of the B-field

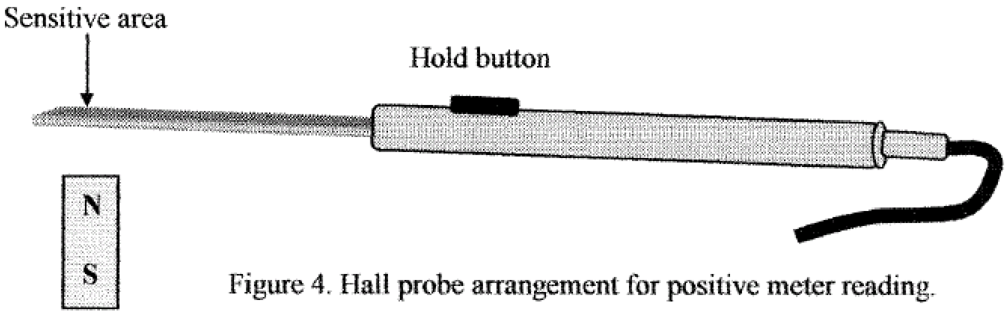

Figure 4. Hall probe arrangement for positive meter reading.

The magnetic field can be measured with the Hall-effect probe provided. In the probe case you will find the probe and the instrument which processes the signals and gives a digital readout. Plug the probe cable into the readout unit before switching the unit on. Do not remove the probe without first turning the unit off.

After pressing the on-key the probe executes a self calibration which takes about 10 seconds. The probe can be used in auto range or you can select the range you wish to work with by pressing the range button until the desired mode of operation is selected. A button on the probe itself can be used as a hold button to freeze the meter reading. Pressing the button a second time releases the hold. The probe measures the component of the field normal to its flat surface. A positive reading results if the probe is oriented with respect to the field as shown in the diagram. (Figure 4).

The probe is a sensitive instrument and can easily resolve 1 milliTesla on the 0-3 Tesla range. The manufacturer claims an accuracy of better than ±1% (DC)at 20ºC with a reproducibility of ±0.5%. The sensitive area of the probe is 0.2mmX0.2mm. Be careful not to damage the probe as it is a delicate instrument. When you have finished using the probe please turn it off, refit the plastic cover and return the probe to its case.

There is another effect that has to be considered. Magnetic fields show hysteresis and hence the field between the pole pieces for a given current flow in the coils depends on whether the current was increased up to the value or reduced from a higher value. Therefore, if you wish to use the current reading as a measure of the magnetic field you must take care to always approach the value from the same direction. You should investigate this effect for yourself.

- *What parameters influence the precision with which the magnetic field is measured? You should estimate here the statistical precision with which you have measured the magnetic field and also the absolute acuracy.*

Interpretation

The measurement of the magnetic field at which the Zeeman components overlap is used to determine the charge-to-mass ratio for the electron in the following way.

Theory: Zeeman Effect. The energy of a system with a magnetic moment μ due to the influence of a magnetic field *B* is given by:-

$$E = -\vec{\mu}.\vec{B}.$$

In an atom the projection of the magnetic moment along the z-axis, due to orbital motion of an electron, is given by:-

$$\mu_z = -\mu_B m_l = {}^{-e\hbar}\!/\!_{2m_e}\, m_l$$

where μ_B is the Bohr magneton and m_l, which can take integral values from $-l$ to $+l$, is the magnetic quantum number of the state. Do not confuse m_l with m_e, the electron mass or m, the order of the interference .

The splitting of atomic energy levels by an applied magnetic field, manifest by the splitting of spectral lines, is know as the Zeeman effect. This is due to the change of energy of a wave function with magnetic moment μ_B in a magnetic field B. If both the energy levels in a transition have non-zero spin/angular momentum, the splitting of both levels has to be taken into account. In general both the spin and orbital angular momenta will give rise to a splitting of the energy levels. In this work the transition selected for study makes use of an l = 1 to l = 0 transition and there is no change in the spin projection. Hence we need only to consider the splitting of the exited state into three levels. Further discussion of the Zeeman effect will be found in any good atomic physics text book. It is not a requirement that you extend your knowledge beyond what is given here.

The energy associated with an atomic magnetic moment, due solely to the orbital motion, in an external field is given by $\Delta E = \mu_B m_l B$. In a more general formulation this energy has to be multiplied by the Lande g factor (g) which takes into account contributions to the energy shift from both the spin and orbital components of the total angular momentum.

Thus $\Delta E = \frac{1}{2}\frac{e}{m_e} m_l \hbar B$.

An accurate determination of the charge to mass ratio of the electron thus requires the determination of the energy shift and the strength of the magnetic field which caused this shift.

The energy difference between the magnetic sub-states is readily found by determining the difference in wavelengths between the light emitted from the different m_l-states.

Theory: Optics The basic theory of the étalon is one of interference between multiply reflected beams. The relevant formula linking the order of interference m, the wavelength λ, the etalon spacing d, refractive index n and angle of incidence θ is

$$m\lambda = 2dn\cos\theta$$

The highest order interference is in the centre of the pattern and successive rings have an order of one less than the previous ring. As we move outwards in the ring pattern both the order and off-axis angle are changing. We are interested in determining the wavelength difference between the Zeeman-split components and so we differentiate the equation with respect to the variables giving

$$m\partial\lambda = -2dn\sin\theta\partial\theta_\lambda \qquad \text{and} \qquad \lambda\partial m = -2dn\sin\theta\partial\theta_m$$

where the subscripts on the $\partial\theta$ indicate a change in angle due to either a change in wavelength or the order of the interference. The three equations given above give

$$\delta\lambda = \frac{\lambda^2\delta m}{2nd\cos\theta}\frac{\partial\theta_\lambda}{\partial\theta_m}$$

The change in order δm is 1 when $\partial\theta_m$ is defined as in figure 3.
The ratio $\partial\theta_m/\partial\theta_\lambda$ can be easily found from Figure 3 when the split and shifted lines from one order overlap with lines shifted in the opposite direction from an adjacent order of interference (you should work out the value of the ratio).
The angles observed are all very small and hence $\cos\theta \cong 1$. The refractive index and the étalon thickness must be known (ask the demonstrator).

Thus an accurate determination of the change in wavelength due to the perturbing magnetic field can be made for the condition of overlap. What is actually needed is the corresponding change in the photon energy.

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- *What is the relationship between the wavelength and energy of a photon? How is a small change in the energy of an atomic transition related to the change in wavelength of the emitted photon?*

Tabulation and analysis of results

Use your value of the magnetic field at overlap to now calculate a value for the charge-to-mass ratio for the electron and an uncertainty on your estimate. You should include both statistical and systematic errors. Compare your value with the expected value and attempt to justify any discrepancy.

Polarisation

For the next part of the experiment you will explore the polarisation of the Zeeman-split components under the two conditions of transverse (as in the first part of the experiment) and longitudinal magnetic field configurations. First you need to understand some terminology.

Linear and Circular Polarization

Linearly polarized light is due to an electric field oscillating along a straight line. This type of polarization can be detected by a Polaroid filter which will let the light through with little attenuation when the electric field vector aligns with the polarizing axis of the filter. By rotating the filter the light intensity is diminished according to the formula $I = I_{max}\cos^2\phi$ where ϕ is the angle between the plane of polarization and the polarizing axis.

When the electric and magnetic field vectors have constant magnitudes but rotate about the propagation axis, the polarization is know as circular polarization. This can be thought of as a linear combination of two waves with linear polarization in orthogonal planes. Two other criteria are also required, namely that the two oscillating waves are 90° out of phase with each other and that the waves have equal amplitude, see figure 5.

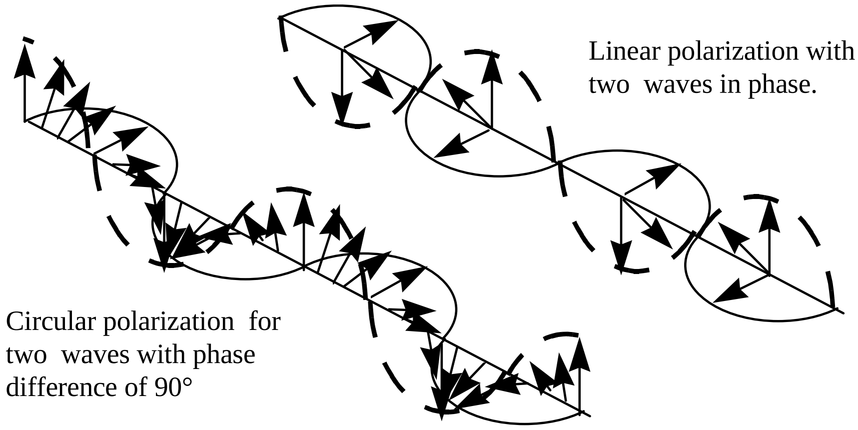

Figure 5. Linear and circular polarization

Circular polarization can be converted to linear polarization with a quarter wave plate. This is made from a material which has a refractive index along one axis different to that along an orthogonal axis. Thus, as light passes through the material of the quarter wave plate, the phase relation between the waves with their polarization aligned along these two axes changes. If, as in the quarter wave plate the thickness of the material is adjusted to give a relative phase change of 90°, then circular polarization will be converted to linear polarization which can then be detected with a linear polaroid filter.

Polarisation of emitted light

A charge moving in a circular orbit emits circular polarization normal to the plane of the orbit and linear polarization in the plane of the orbit. You are now going to relate this to the orbital motion of the excited electron, at least in a classical sense.

In the transverse-field configuration place a linear polariser (Polaroid) between the light source and the entrance slit of the spectrometer. Vary the magnetic field and identify which if any of the three components of the split line are sensitive to the orientation of the Polaroid.

- *Use your observations to help you understand the Zeeman effect*

Now change the orientation of the magnet to the longitudinal configuration. You will have to remove some bars that pass down the axis of the magnet. Note which bar comes out of which pole piece and do not lose them. You should replace the bars in the correct pole piece when you have finished. You will find this time that there are only two magnetically split components to each line. Again analyse the polarisation of the components this time using both a Polaroid and a quarter-wave plate.

- *Explain your observations in terms of the transverse nature of light oscillations and the Zeeman effect.*