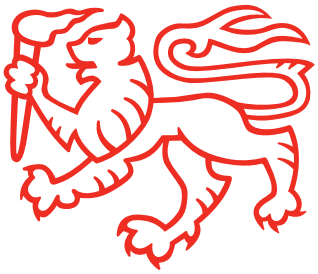


UNIVERSITY of TASMANIA

PART III LABORATORY WORK

KYA312/322

THE ZEEMAN EFFECT IN MERCURY

Last compiled 2025-07-29

Safety

This experiment involves the use of a strong static magnetic field. A serious hazard is posed to anyone with ferrous surgical implants and/or bioelectronic devices. Magnetically susceptible jewellery should be removed, and particular care should be taken with any form of magnetic storage media and analogue watches, as exposure to the field may result in permanent damage.

The mercury discharge lamp emits a substantial fraction of its spectral power in the ultraviolet, which can be harmful to your skin and eyes after prolonged exposure (in the same way sunburn is not awesome for you). In addition, since you will be working in a dark room, your pupils will be dilated, allowing more ultraviolet light to hit your retina. For this reason, the mercury lamp is shielded by some black felt. Leave this cover on while the lamp is on. Be sure to also wear the provided safety glasses for extra protection. Ultraviolet light is relatively easily shielded by most glasses.

Outline

Summary

The Zeeman effect is the splitting of a single spectral line into multiple, discrete components in the presence of a magnetic field. It occurs because the magnetic field interacts with the magnetic moments of electrons, shifting the energy levels of atomic orbitals.

Using a Fabry-Perot interferometer and a well-aligned optical system, we will investigate the Zeeman effect in Mercury. In particular, we will observe the splitting of the 546.1 nm green spectral line. The resulting interference patterns will be reduced to derive a value for the Landé g-factor.

Experiment Objectives

- Using the properties of the emission spectra of Mercury under an externally applied magnetic field, determine the wavelength and energy splitting as a function of the magnetic field strength and if possible, derive a value for the Landé g-factor.
- Understand basic optical configurations and procedures for optical calibration and alignment.
- Explore the properties of a Fabry-Perot etalon and how it is used in high-resolution spectroscopy.

Background Theory

There have been many notable scientific advances in the discovery of atomic structure. The reader may be aware of a few of the following noteable advancements: The discovery of negatively charged atomic particles (electrons) by J.J. Thomson in 1897 using a Cathode Ray Tube; Ernest Rutherford's gold foil experiment in 1911 which showed that atoms largely empty space, with the positive charge concentrated in a nucleus; Niels Bohr adapts Rutherford's nuclear structure to Max Planck's quantum theory and presents the Bohr model of the atom in 1913; James Chadwick discovers the neutron through beryllium bombardment in 1932; Maria Goeppert Mayer develops the model of nuclear structure in 1949.

The Zeeman effect (the subject of this experiment) was first observed in 1896 by Dutch physicist Pieter Zeeman and has been pivotal in the refining our understanding of atomic structure and quantized energy levels. Although not initially understood at the time, the Zeeman effect reveals the presence of fine energy level splitting due to electron spin and magnetic interactions, which are not accounted for in simpler atomic models. It thus provides important experimental evidence for quantum mechanical concepts like spin, magnetic moments, and angular momentum coupling.

The Zeeman Effect

The original Zeeman effect experiment involved placing a piece of asbestos (not recommended for today's experimentation) soaked in salt water into a Bunsen burner and setting it in front of a diffraction grating. When no magnetic field was used, two spectroscopic lines associated with the Sodium emission could be easily observed. Zeeman exposed the sodium flame to a strong magnetic force by placing it in between the poles of a strong (10 kilogauss) electromagnet. Zeeman observed a broadening of the spectral lines which were previously sharply defined. Zeeman switched

the source from Sodium to Cadmium, and that's when the magic really happened. Figure 1 shows what they found; previously singular spectral lines had been split further.

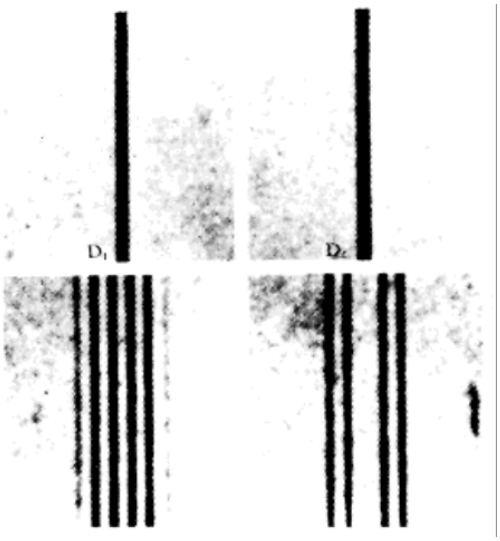


Figure 1: An image Pietr Zeeman showed as part of his 1902 Nobel Prize lecture. Here, the observed energy level splitting is shown for Cadmium. In the top row of this image, the spectral lines of Cadmium in the *absence* of a magnetic field are shown. Underneath, the hyperfine structure that results from the application of an external magnetic field can be seen.

Qualitatively, the Zeeman effect occurs because electrons orbiting the nucleus have a magnetic dipole moment due to their angular momentum. Without a magnetic field, some electron energy levels are degenerate - that is, they have the same energy. When a magnetic field is applied, the electrons gain additional energy depending on how their magnetic dipole aligns with the field. The amount of energy shift depends on the orientation of the electron's magnetic moment relative to the magnetic field, and can be positive, negative, or zero. As a result, the original degenerate energy levels split into multiple distinct levels. This creates new possible transitions between energy levels, leading to additional spectral lines in the atomic spectrum.

Atomic Energy Levels and Degeneracy

Terms and Definitions

Throughout, we will use the following notation and variables:

- **Principle quantum number** n - this is the main energy level occupied by the electron
- **Angular momentum quantum number,** l - this describes the orbital shape of the electron. Its value depends on the value of n. l can take positive values from 0 to $(n-1)$. In general, s sublevels will always have $l = 0$ while p sublevels will have $l = 1$.
- **Orbital angular momentum vector, L** - The magnitude of the orbital angular momentum is $|\mathbf{L}| = \sqrt{l(l+1)}\hbar$. So, for each l, there are $2l + 1$ possible orientations of the angular momentum vector, all with the same magnitude but different z-components.
- **Magnetic quantum number,** m_l - this describes the orbital orientation. For a given value of l, there can be a total of $(2l + 1)$ values of m_l and it can take on the values $l, l-1, l-2, ..., -l$.

- **Spin quantum number**, s (not to be confused with the s-sublevel) - The spin quantum number ss is an intrinsic property of particles, meaning it does not change with the particle's motion or position. For electrons, the spin quantum number is always $\frac{1}{2}$.
- **Magnetic spin quantum number**, m_s - the projection of the spin angular momentum vector along an axis (usually the z-axis). For $s = \frac{1}{2}$, the possible values of m_s are

$$m_s = +\tfrac{1}{2} \text{ (spin-up)}$$

$$m_s = -\tfrac{1}{2} \text{ (spin-up)}$$

- **Spin Angular Momentum, S** - The spin angular momentum vector refers to the intrinsic angular momentum of an electron (or any other particle with spin), which is a fundamental property of particles in quantum mechanics. Unlike orbital angular momentum (which arises from an electron's motion around the nucleus), spin angular momentum is an intrinsic, internal property of the electron.

In quantum mechanics, the energy levels of an atom arise from solutions to the time-independent Schrödinger equation applied to the Coulomb potential of the nucleus. For a hydrogen-like atom, the energy eigenvalues depend primarily on the principal quantum number n, and are given by:

$$E_n = \frac{-13.6\text{eV}}{n^2}$$

These energy levels depend only on the principal quantum number n, but not on the orbital angular momentum l or the magnetic quantum number m_l. As a result, all states with the same n but different l and m_l values have the same energy - they are degenerate.

The total number of degenerate states for a given n is:

$$\sum_{l=0}^{n-1}(2l+1) = n^2$$

In more complex atoms or when external fields are applied (such as magnetic or electric fields), the spherical symmetry is broken and the degeneracy is partially or fully lifted, meaning that energy levels once equal become distinct and can be observed as a shift in the previously single spectral line.

Angular Momentum and Magnetic Dipoles

An understanding of magnetic dipoles and angular momentum is fundamental to the theoretical framework of the Zeeman effect because the phenomenon arises from the interaction between an atom's intrinsic magnetic moments and an external magnetic field. We shall refresh a few important concepts in this section.

The total angular momentum vector $\mathbf{J}$ of an electron is a combination of the orbital angular momentum vector $\mathbf{L}$ and the spin angular momentum vector $\mathbf{S}$ such that

$$\mathbf{J} = \mathbf{L} + \mathbf{S} \tag{1}$$

For both the orbital and spin angular momenta, an associated magnetic dipole arises. As a reminder, magnetic dipole moments (or simply "magnetic dipoles") are vector quantities that describes an object's magnetic properties. Specifically (and of particular interest to this lab), they describe the objects tendency to interact with an external magnetic field.

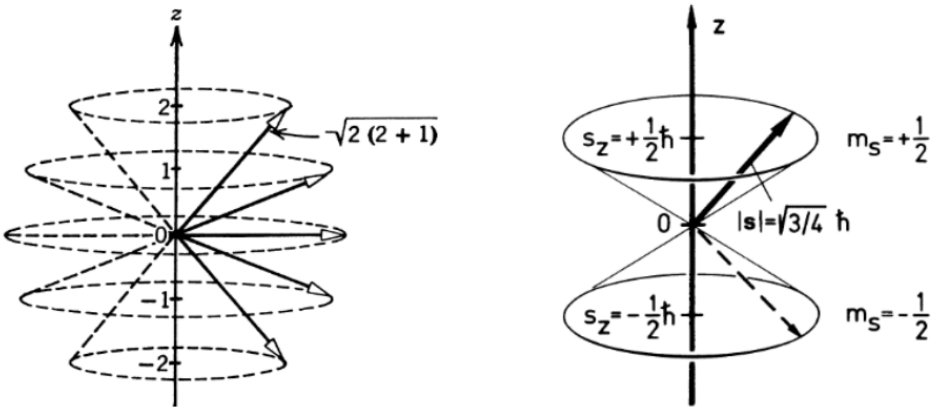


Figure 2: Dipoles

From the classical point-of-view, an electron of mass m_e and charge q_e circulating around a nucleus can be described as a tiny current loop with an associated magnetic dipole moment

$$\mu_L = \frac{-q_e}{2m_e}\mathbf{L} \tag{2}$$

Where the negative sign reflects the negative charge of the electron. The magnitude of the angular momentum is quantized, and its z-component takes on discrete values $L_z = m_l\hbar$.

In addition to orbital motion, electrons possess intrinsic angular momentum known as spin. This gives rise to a second magnetic moment, the spin magnetic moment $\mu_\mathbf{S}$, given by:

$$\mu_S = g_s\frac{q_e}{2m_e}\mathbf{S} \tag{3}$$

Where $g_s \approx 2$ is the electron spin g-factor.

Interactions with a magnetic field

There are two “flavours" of Zeeman effect that pop up in the relevant literature on the subject. The “normal" Zeeman effect and the “anomalous" Zeeman effect. Generally, the difference between the two depends on whether spin is involved in the magnetic splitting of the atomic energy levels.

In the case of the “normal effect" we ignore spin (a non-relativistic quantum mechanical perspective) and we consider Zeeman splitting in terms of transitions between

If an external magnetic field is present, a torque is exerted, causing the magnetic moment to precess about the field lines. The energy associated with the interation of μ_L with $\mathbf{B}$ is given by

$$\Delta E = -\mu_\mathbf{L}\cdot\mathbf{B} = -\mu_z B = -\frac{q_e}{2m_e}L_z B = -\frac{q_e}{2m_e}m_l\hbar B = m_l\mu_B B \tag{4}$$

where $\mu_z = \frac{q_e}{2m_e}L_z$ is the projection of the magnetic moment along the field axis, which we commonly label as z. μ_B is the Bohr magneton and has values 9.274×10^{-24} J T^{-1} or 5.788×10^{-5} eV T^{-1}.

Equation 4 is clearly dependent on the orientation of $\mathbf{L}$ and $\mathbf{B}$. If all orientations of $\mathbf{L}$ and $\mathbf{B}$ are allowed then we would expect to see a continuous range of E. A spectral line would then be observed to broaden by an amount proportional to the field strength. However, we instead observe a splitting of the spectral lines into several *discrete* components. This suggests the spatial quantisation of $\mathbf{L}$.

Since there are $2l + 1$ allowed values of m_l, each energy level will split into $2l + 1$ levels.

The total magnetic moment has both spin and angular momentum,

$$\mu = \frac{q_e}{2m_e}(2\mathbf{S} + \mathbf{L}) = \frac{e}{2m_e}(\mathbf{J} + \mathbf{S}) \tag{5}$$

and the shift in energy levels is

$$\Delta E = -\mu \cdot \mathbf{B} = -\frac{e}{2m_e}(\mathbf{J} + \mathbf{S}) \cdot \mathbf{B} = -g_L \frac{e}{2m_e} J_z B = -g_L \mu_B m_j B \tag{6}$$

g_L is called the Landé g-factor. It's a dimensionless quantity that characterizes the energy levels of electrons in a magnetic field.

$$g = 1 + \frac{\mathrm{j(j+1)} + \mathrm{s(s+1)} - \mathrm{l(l+1)}}{2\mathrm{j(j+1)}} \tag{7}$$

(8)

The Landé g-factor

The Landé g-factor is a dimensionless quantity that characterizes the energy levels of electrons in a magnetic field.

The aim of this experiment is to determine the wavelength and energy splitting as a function of the magnetic field strength and derive a value for the g-factor. Your results should be compared to the theoretical expression

$$g = 1 + \frac{\mathrm{J(J+1)} + \mathrm{S(S+1)} - \mathrm{L(L+1)}}{2\mathrm{J(J+1)}} \tag{9}$$

Selection rules and polarization of emitted photons

The transition between Zeeman shifted states must obey conservation laws that determine which transitions are "allowed" and which are "forbidden". The allowed transitions are dictated by a set of selection rules:

$$\begin{gathered} \Delta L = 0, \pm 1 \\ \Delta S = 0 \\ \Delta J = 0, \pm 1 \\ \Delta m_j = 0, \pm 1 \end{gathered}$$

$\Delta m_j = \pm 1$ transitions are called σ transitions, while $\Delta m_j = 0$ transitions are called π transitions.

Observing the Energy Shift - Fabry-Perot Etalons

In order to observe the hyperfine splitting of spectral lines in the presence of a magnetic field, one needs a device that is highly sensitive to small changes in wavelength in order to image the splitting. One such device is a Fabry Perot etalon. This is a device that consists of two parallel surfaces with semi-transparent, highly-reflective coatings, separated by a cavity of thickness t. Light that enters the etalon undergoes a series of reflections with some light emerging on each reflection as shown in Fig. 3. The the net effect of this instrument is to split a single beam of light into multiple beams that then interfere with one another. When the extra optical path length traveled by a reflected beam matches an integer multiple of the light's wavelength, the resulting interference is constructive. In essence, the multiple reflections within the cavity interact similarly to light passing through a multiple-slit grating: as the number of reflections increases, the interference peaks become narrower and more well-defined.

Terms and Definitions

If you do wider reading on the subject, you will likely come across the term 'Fabry-Perot Interferometer'. The terms 'etalon' and 'interferometer' are often used interchangeably but an etalon is essentially an interferometer where the distance between the two surfaces is fixed.

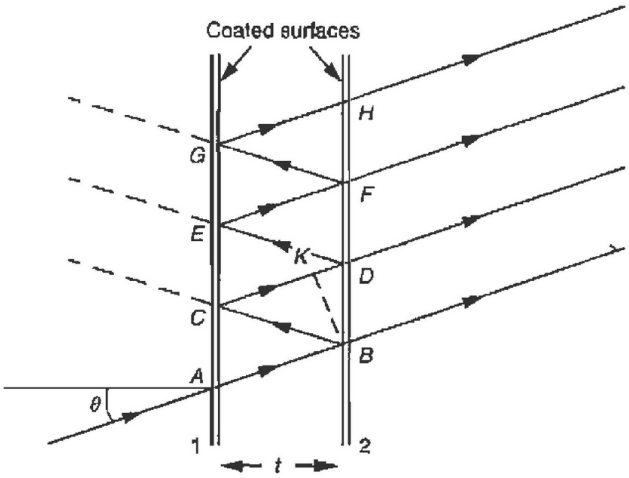


Figure 3: The path of a ray travelling through the parallel plates of a Fabry-Perot etalon

Consider parallel rays incident on the Fabry-Perot plates at an angle of incidence θ. Standard geometry gives the path length difference between successive reflections as $2t\cos\theta$ for an etalon cavity thickness t. The corresponding optical path difference must then be a whole number m of wavelengths in order for constructive interference (i.e. bright fringes) to occur. If the etalon cavity is filled with some medium of refractive index, n then the condition for constructive interference is

$$2tn\cos\theta = m\lambda. \tag{10}$$

And we shall label the order of the first ring $m_0 = \frac{2nt}{\lambda}$ so equation 10 can also be written as $m = m_0\cos\theta$. Since θ is considered small we may then write,

$$m = m_0\left(1 - \frac{\theta^2}{2}\right) \tag{11}$$

While m describes the order of the bright fringes and takes integer values, in general, m_0 is not an integer. You are asked to explain why this is the case below.

The order of the first bright fringe (counting from the center) will be $m_1 = m_0\cos\theta$ and less than m_0. Let us then let $m_1 = m_0 - \epsilon$ where ϵ is a fractional excess lying between 0 and 1. In general, for the p^{th} ring,

$$m_p = (m_0 - \epsilon) - (p - 1) \tag{12}$$

To observe the ring structure produced from the Fabry-Perot etalon, the parallel rays (B, D, F, K in Fig. 3) leaving the etalon are brought into focus by a lens of focal length, f as shown in Fig. **??**. The radius of the rings on a detector a distance f away is then

$$r = f \tan\theta \approx f\theta \tag{13}$$

where θ is the same angle as in equation 10.

Combining equations 13, 11 and 12 we can obtain

$$r_p^2 = \frac{2f^2}{m_0}((p-1) + \epsilon) \tag{14}$$

It is easy to show that the difference between the squares of the radii of adjacent rings is a constant,

$$r_{p+1}^2 - r_p^2 = \frac{2f^2}{m_0} \tag{15}$$

The fractional excess ϵ can be measured from the radii of the rings. It follows from 14 that

$$\frac{r_{p+1}^2}{r_{p+1}^2 - r_p^2} - p = \epsilon \tag{16}$$

Using obtained data from the Fabry-Perot interferometer, you will be able to experimentally determine the wavelength splitting and derive a value for the Landé g-factor. In the appendix, notes on how to reduce the data from a Fabry-Perot interferometer are given.

Theory Exercises

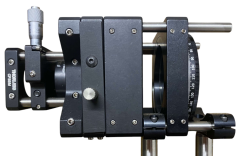
Using the content in the background theory, provided appendix material and your own independent research, complete the following exercises for inclusion in your logbooks.

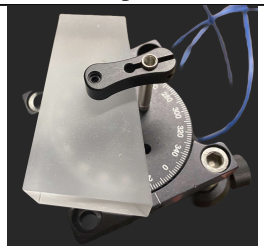
Theory Exercises

1. The 546.1 nm green line in mercury is the result of a transition from the $^3S_1$ (6s7s) energy level to a $^3P_2$ (6s6p) level. Sketch and label the energy level splitting with and without an applied magnetic field for the 546.1 nm spectral line. What is the expected splitting pattern?
2. Thinking about the Fabry-Perot etalon, suggest why this in an important inclusion when investigating hyperfine splitting?
3. Using the etalon geometry in Fig. 3, show that the path-length difference of two parallel rays through an etalon of fixed thickness, t is $2t\cos(\theta)$.
4. Why is the central order, m_o generally not an integer as described in the Fabry-Perot Etalon section above?
5. Show that for the p^{th} ring, $m_p = (m_0 - \epsilon) - (p - 1)$

Apparatus

To observe the Zeeman effect in Mercury and obtain a final measurement of the Landé g-factor, we require an optical system that has the capability to resolve the splitting in the spectral lines. The optical bench in the laboratory has a number of components, including lenses, a camera and a Fabry-Perot Etalon. In Table 1, below, a photograph of each component is provided along with a description of useful specs.

	Unit for collimating the emission from the mercury lamp. Consists of a diffuser, slit, longpass filer (400 nm), 60mm planar convex lens, adjustable polariser for filtering out different polarisation states.
	Fused silica etalon. 450-500nm, finesse > 30.
	Small doublet lens
	Variable-width slit
	Big lens

Component	Description
	Constant deviation prism.
	Camera

Procedure

This experiment can be broken down into a few steps.

1. Find and plot the relationship between magnetic field and current.
2. Align the optical system and setup the bench to obtain sharply focused ring patterns.
3. Determine the thickness of the Fabry Perot Etalon by looking at the produced ring pattern.
4. Determine the wavelength and energy splitting as a function of the magnetic field strength and, if possible, calculate the value of the g-factor.

1. Relationship between magnetic field and current.

When we are investigating the Zeeman effect, it is advisable to keep the Mercury lamp covered for the safety reasons outlined at the start of this document. This means, that we will want to determine a relationship between the magnetic field incident on the lamp and the current fed into the Helmholtz coils.

Important - When working with the power supply and Helmholtz coils, make sure the power supply knob is turned all the way down to zero before turning the power supply to the coils on or off. This prevents any unwanted discharge.

Task 1

Produce a plot of B vs. I.
You are provided with a Hall probe which can be used to get a reading of a nearby magnetic field. Follow the probe manual to get this setup up.

2. Aligning the optical system.

A crucial ingredient to performing this experiment is the proper alignment of the optical equipment. Ultimately, we need a chain of optical components that allow us to see the ring separation from the mercury lamp with enough resolution to be able to detect the ring splitting when we get to incrementally increasing the magnetic field. The initial problem here is that the mercury lamp isn't very bright and so alignment of the optics will be difficult. For this reason, we will begin using a laser.

To begin our setup of the apparatus, we want to establish the conditions we need to meet. In this setup section we're ultimately looking for an optical chain that takes an **uncollimated** light source (the mercury lamp), feeds it through something that can produce the ring pattern and then focus that pattern onto a detector (the camera) so we can study it.

To start with, treat the provided white card as the detector. You will be able to see the ring pattern on this and it will help you get an idea for where to place the camera (the camera has a substantial zoom so detecting the rings will only work if it is well positioned). Once you have a focused ring pattern on the card, you can replace it with the camera and make fine adjustments.

Task 2

Using some (you won't need all) of the optical components and their descriptions in the Apparatus section of these notes, design an optical chain that will allow you to study the interference ring pattern from the mercury lamp.
Remember to handle the optical components with care and do not touch the optical surfaces. Some optical surfaces are damaged by the natural oil on your skin.

Task 3

Now put this plan into motion. To start with, we want to feed the light from a laser through the optics to achieve a sharp image of the interference rings from the laser. It is likely you'll need to carry out many fine adjustments as you go through this process. Record your observations of the ring pattern from the laser. You should aim for the sharpest image you can get.

Task 4

You should now be in a position to transfer your optical setup to the mercury lamp. Position the start of the optical chain close to the lamp to capture as much light as you can.

Without turning on the magnetic field, document your observation of the ring pattern for the mercury lamp.

3. Determining the thickness of the Fabry-Perot etalon

A key missing quantity is the thickness of the Fabry-Perot etalon.

Task 5

Using your understanding of the Fabry-Perot etalon and the equations given, determine how the etalon cavity thickness t can be obtained from measurements of the produced ring patterns.

4. Measuring the energy splitting and deriving the Landé g factor

We're now into the meat of this experiment. At this point, we should have a well-aligned optical system that can display sharp images. It's now time to introduce the magnetic field and work towards obtaining a value of the Landé g-factor.

Task 6

Turn on the power supply to the Helmholtz coils and start to increase while observing the changes to the ring pattern. Document your observations. Do you see the ring pattern split as you increase the magnetic field?

Task 7

Using the information contained in the background section and in the appendix from Mellissinos, reduce the data from the optical system. Determine the wavenumber separation as a function of magnetic field. Finally, can you obtain an experimental value for the Land/'e g-factor?

References

Appendices