The Zeeman Effect in Neon

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Contents

1 Learning Outcomes

1. Study the use of several advanced pieces of equipment, including a Fabry-Perot interferometer in an experimental setting.

2. Observe the splitting of the spectral lines of neon light in an external magnetic field.

3. Calculate the value of the Bohr magneton (a unit used to describe the magnetic moment of the electron).

2 Introduction

The Zeeman effect [1, 2] is the splitting of electronic energy levels by an applied magnetic field. In the years following Zeemans original observations (1896) both classical and quantum explanations of the effect were developed, but a fully satisfactory theory only became available after the discovery of electronic spin and the formulation of quantum mechanics in the 1920s.

Since that time, the Zeeman effect has gone on to be used in several different situations, largely in astrophysics [3]. This effect allowed for the first observation of magnetic fields in sunspots and the first indication of extraterrestrial magnetic fields. It has gone on to become the best method for directly observing astrophysical magnetic fields.

3 Theory

The core principle of the Zeeman effect, and the reason its discovery was so important to the development of physics, is that it perfectly illustrates the phenomenon of space quantization. This means that the angular momentum of the atom **L** can only assume a set of discrete orientations with respect to an external magnetic field **B**.

We can start with the Hamiltonian of this system using perturbation theory

$$H = H_{atom} + H_z \tag{1}$$

where the unperturbed Hamiltonian (H_{atom}) is modified by the perturbation due to the system being placed in an external magnetic field (H_z). Using the magnetic moment μ and the external field B

$$H_z = -\vec{\mu} \cdot \vec{B} \tag{2}$$

The scalar product of the dipole moment and the external magnetic field can then be written

$$H_z = -\frac{q}{2m}\big(\vec{L} + g\vec{S}\big)\vec{B} \tag{3}$$

We can now assume that the magnetic field is oriented along the z-direction and has strength B^{ext} while inserting the known values for g (2 for this system) and the electron mass and charge.

$$H_z = \frac{e}{2m_e}\big(L_z + 2S_z\big)B^{ext} \tag{4}$$

It is obvious [1] from this equation that the Eigenfunction ψ_{nlm} of the atomic Hamiltonian has Eigenvalues which also satisfy L_z with Eigenvalues $\hbar m_\ell$.

This means that the values satisfying this equation are then

$$|H_z| = \frac{e}{2m+e}\hbar m_\ell B^{ext} \tag{5}$$

or, making the substitution for the Bohr magneton ($\mu_B = \hbar e/2m_e$)

$$|H_z| = \mu_B m_\ell B^{ext} \tag{6}$$

where m_ℓ = -ℓ, -ℓ+1, ... , +ℓ-1, +ℓ.

A favourable system for studying the Zeeman effect is a neon gas discharge, since the prominent yellow line at 585 nm shows the normal Zeeman effect and other lines in the visible spectra show both normal and anomalous effects. The yellow emission is between the singlet $^1S_0$ of $2p^5\,3p$ and the triplet $^1P_1$ of $2p^5\,3s$.

In the present experiment, the required high resolving power is provided by a Fabry-Perot interferometer. This instrument was originally developed for high-resolution spectroscopy and is now used as the resonant cavity in almost all lasers; although, for this purpose the reflecting surfaces are usually curved. The Fabry-Perot interferometer makes use of multiple reflections

[1] Once this has been done many times and drilled into one's head

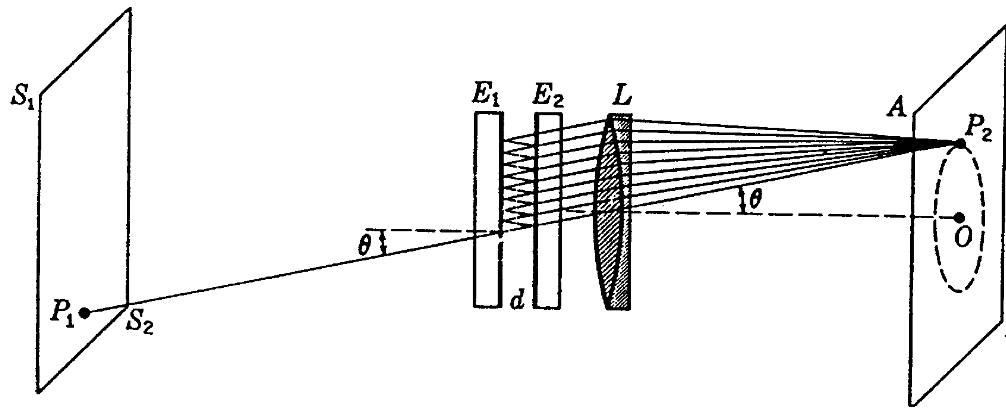

Figure 1: Diagram of monochromatic light forming a ring on surface B

between two partially reflecting plane parallel surfaces separated by a distance d. A beam of light incident at an angle θ from the axis will interfere constructively if the condition

$$2d \cos\theta = m\lambda \tag{7}$$

is satisfied, with m a large integer of order $2d/\lambda$ [1]. Monochromatic light incident at all angles therefore forms a series of rings, which can by very sharp if the reflectivity is high and the surface are accurately flat and parallel. Note that the rings are not equally spaced; analysis shows that a plot of ring diameter squared versus the ring number (the first visible ring is number 1) should produce a straight line.

If light source contains two nearly equal wavelengths λ_1 and λ_2, with λ_2=λ_1 + $\Delta\lambda$, there will be two sets of rings, closely spaced. An important parameter for any interferometer is the value of $\Delta\lambda$ that causes the nth ring of wavelength λ_1 to coincide with the $(n-1)$th ring of λ_2. For the Fabry-Perot interferometer, the result is

$$\Delta\lambda = \lambda_1^2/2d, \tag{8}$$

which is a very small quantity for typical spacings of $d \sim 1$ cm. For the interferometer used in this experiment, the corresponding frequency difference between orders, called the free spectral range, is given as 30.0 GHz.

1.	Neon Discharge Tube	7.	Fabry-Perot Interferometer
2.	Magnet	8.	Digital Camera on Stand
3.	Digital Multimeter	9.	Hall Probe Control
4.	Discharge Tube Power Supply	10.	Probe
5.	Magnet Power Supply	11.	Digital Multimeter
6.	Tunable Filter		

Table 1: Equipment list for Zeeman effect lab

4 Equipment

The equipment available for this lab is listed below.

5 Designing Your Lab

When putting together the apparatus you will use for conducting your experiment, you should keep the following points in mind:

Theoretical Considerations

1. How could you test the hypothesis that g=1? How could you find the e/m ratio? Can you do both?

2. How can you check the polarizations of the Zeeman components?

3. What is the largest source of uncertainty in the lab?

Experimental Considerations

1. What frequency should be the main focus of the experiment? How will you remove the other lines?

2. In what orientation should the magnetic field be relative to the spectrometer?

3. How many different values for the magnetic field are required?

4. Is the magnetic field linear with the applied current? Does hysteresis in the control have any effect?

Predictions

1. What is the effect of increasing the applied magnetic field?

2. Is there a threshold value of the magnetic field at which the splitting of the lines will happen? If so, what is it?

3. What is the effect on the results if the magnetic field is not constant throughout the entire sample?

Design

1. The magnetic field will need to be calibrated using the available equipment, so the best way to do that should be included in the design.

2. What is the effect of the uncertainty in the measurement of the magnetic field?

3. What is the dominant source of uncertainty in this lab? Is there any way to reduce this source?

References

[1] Physical Optics, *Jenkins and White*, Chapter 29

[2] Modern Experiments in Physics, *Mellissinos*

[3] L.Widrow, *Origin of galactic and extragalactic magnetic fields*, Rev. Mod. Phys 74 (775), July 2002