THE ZEEMAN EFFECT

OBJECT: To measure how an applied magnetic field affects the optical emission spectra of mercury vapor and neon. The results are compared with the expectations derived from the vector model for the addition of atomic angular momenta. A value of the electron charge to mass ratio, e/m, is derived from the data.

Background: Electrons in atoms can be characterized by a unique set of discrete energy states. When excited through heating or electron bombardment in a discharge tube, the atom is excited to a level above the ground state. When returning to a lower energy state, it emits the extra energy as a photon whose energy corresponds to the difference in energy between the two states. The emitted light forms a discrete spectrum, reflecting the quantized nature of the energy levels. In the presence of a magnetic field, these energy levels can shift. This effect is known as the Zeeman effect.

Zeeman discovered the effect in 1896 and obtained the charge to mass ratio *e/m of* the electron (one year before Thompson's measurement) by measuring the spectral line broadening of a sodium discharge tube in a magnetic field. At the time neither the existence of the electron nor nucleus were known. Quantum mechanics was not to be invented for another decade. Zeeman's colleague, Lorentz, was able to explain the observation by postulating the existence of a moving "corpuscular charge" that radiates electromagnetic waves. (See supplementary reading on the discovery)

Qualitatively the Zeeman effect can be understood as follows. In an atomic energy state, an electron orbits around the nucleus of the atom and has a magnetic dipole moment associated with its angular momentum. In a magnetic field, it acquires an additional energy just as a bar magnet does and consequently the original energy level is shifted. The energy shift may be positive, zero, or even negative, depending on the angle between the electron magnetic dipole moment and the field. Due to the Zeeman effect, some degenerate atomic energy levels will split into several levels with different energies. This allows for new transitions which can be observed as new spectral lines in the atomic spectrum. In this experiment we will study the Zeeman effect in mercury and neon for which the theory is relatively simple.

THEORY:

Classically, an electron of mass m_e and charge e orbiting the nucleus is described as a tiny current loop that produces a magnetic dipole moment, $\boldsymbol{\mu}$, which is proportional to its orbital angular momentum $\boldsymbol{L}$:

$$\boldsymbol{\mu} = \frac{e}{2m_e}\mathbf{L} \tag{1}$$

In the presence of a magnetic field **B** the dipole experiences a torque due to the Lorenz force, $\frac{d}{dt}\mathbf{L} = \boldsymbol{\mu} \times \mathbf{B}$. This slightly changes the orbit resulting in the energy shift:

$$\Delta E = -\boldsymbol{\mu} \cdot \mathbf{B} = -\mu_z B = -\frac{e}{2m_e} L_z B \qquad (2)$$

Where $\mu_z = \frac{e}{2m_e} L_z$ is the projection of the magnetic moment along the field axis, which we label as z. The change in energy is thus proportional to the projection of the orbital angular momentum along the field axis L_z.

Recalling that the magnetic moment is normal to the plane of the orbit, this tells us that for orbits that are perpendicular to the magnetic field ΔE is either positive or negative depending upon whether the motion of the electron is clockwise or counter-clockwise. If the field lies in the plane of the orbit, the net torque is zero and $\Delta E = 0$.

Quantum mechanical description. In order to understand the Zeeman effect we must turn to the quantum mechanical description of the problem. We start by considering hydrogen which has a single electron. The magnitude of the orbital angular momentum **L** of an electron in a state with principal quantum number n is given by: $L = \hbar\sqrt{l(l+1)}\hbar$ where $\hbar$ = h/2π is the reduced Planck constant. The integer $l = 0,1.. < n$ is called the orbital quantum number and it is usually labeled as S, P, D,F for l=0,1,2,3 respectively. When the atomic potential seen by the electron is purely Coulombic as in the Bohr atom, V(r)~1/r , the energy of the electron only depends on the value of n, $E_n = -\frac{Ryd}{n^2}$ where Ryd =13.6eV. In particular the electron energy does not depend on the angular momentum. As a result, there are multiple possible atomic orbits all with the same energy but with different values of the angular momentum. This is called degeneracy. In general however the atomic potential deviates from the pure 1/r dependence resulting in a reduced degeneracy where states with different values of l have slightly different energies. For each value of n there can then be as many as n energy sub-levels with different values of l (0,1..n-1). These sub-levels can then be labeled as nl. Associated with each of these sub-levels there will be 2l+1 possible states with different projections of the angular momentum along a given axis, $L_z = \hbar m$, **with** $m = -l,-l+1,..,l$. In the absence of a magnetic field to define a preferred axis these states will all have the same energy resulting in a 2l+1 fold degeneracy for each nl sub-level. When taking into account the internal spin angular momentum of the electron, S=1/2, which we discuss later, this degeneracy becomes 2(2l+1).
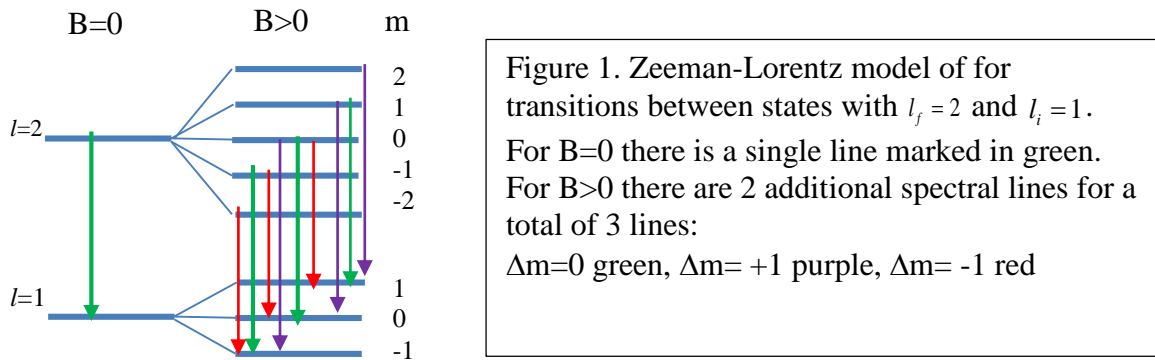
Zeeman-Lorentz theory. This model which explains the Zeeman splitting in terms of transitions between levels with different values of L_z in a magnetic field, ignoring the spin angular momentum of the electron, is rarely observed. Nevertheless the model captures the essence of the physics underlying the effect.

A magnetic field lifts this degeneracy by the Zeeman shift:

$$\Delta E_m = -\frac{e}{2m_e}\hbar m B \equiv m\mu_B B \quad m = -l, -l+1, ..l \tag{3}$$

Here $\mu_B = .9274 \times 10^{-23} J/T = 5.788 \times 10^{-5} eV/T$ is called the Bohr magneton. As a result each nl sub-level splits into $2l+1$ levels with equal spacing of $\mu_B B$.

The light emitted from the gas in a discharge tube is generated when electrons make electron-dipole transitions from an initial state with quantum numbers n_i, l_i, m_i to a lower energy state with n_f, l_f, m_f. When an electron makes such a transition, it emits a single photon which carries away an angular momentum of $\hbar$. The selection rules for electron dipole transition are dictated by the conservation of angular momentum so that transitions can only occur between states where $\Delta l = l_f - l_i = \pm 1$ and $\Delta m = m_f - m_i' = 0, \pm 1$.

Figure 1. Zeeman-Lorentz model of for transitions between states with $l_f = 2$ and $l_i = 1$.
For B=0 there is a single line marked in green.
For B>0 there are 2 additional spectral lines for a total of 3 lines:
Δm=0 green, Δm= +1 purple, Δm= -1 red

In the example shown in Figure 1 the nine different transitions allowed by the selection rules produce only three lines. Convince yourself that this would be the case regardless of the value of l_i. The spectral lines produced in this case were predicted by Zeeman and Lorentz and are called the "normal" Zeeman effect.

The anomalous Zeeman Effect. In practice the normal three-line Zeeman effect is not commonly observed. If a spectrometer with high resolution is used, it is frequently found that the magnetic field splits the spectral lines into more than three components and even when the three line pattern is observed, the splitting increases more rapidly with applied field than predicted by the Zeeman-Lorentz theory. This "anomalous" Zeeman effect was not explained until it was realized that, in addition to the orbital angular momentum, electrons possess spin angular momentum **S** with quantum number $s=\frac{1}{2}$. The total angular momentum of the electron is thus **J=L+S** and the corresponding total angular momentum quantum number is given by the standard rules ("triangle" rule) of addition of angular momenta $j= l+s, l+s-1, ..., |l-s|$. The projection of **J** on the z axis, J_z takes values $\hbar m_j$ where $m_j = j, j-1, ..., -j$. According to theoretical predictions by quantum electrodynamics as well as experimental observations the spin magnetic moment is given by:

$$\boldsymbol{\mu} = g\frac{e}{2m_e}\mathbf{S} \tag{4}$$

where g = 2.0023. For the purposes of this discussion we take the g-factor to be exactly 2. As a result, the magnetic moment of an electron that has both spin angular momentum **S** and orbital angular momentum **L** is given by:

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

And the Zeeman shift in this case is thus

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

If the value of g were g=1 then $\mathbf{\mu}$ would have been parallel to **J** and its projection along the magnetic field would have been proportional to J_z. In this case the Zeeman splitting between levels would have been as before $\Delta E_m = m_j \mu_B B$ independent of L, S or J. However since for g=2, $\mathbf{\mu}$ is no longer parallel to **J** we have to calculate its projection on the z axis using operator algebra (see A. Melissinos, Experiments in Modern Physics or any standard quantum mechanics text for the derivation). The result is $\mu_z = g_L \frac{e}{2m} J_z$

where g_L is called the Lande g-factor and is given by

$$g_L = 1 + \frac{J(J+1)+S(S+1)-L(L+1)}{2J(J+1)}. \tag{7}$$

We can now combine Eqs. (6) and (7) to obtain the Zeeman shift:

$$\Delta E = -\mathbf{\mu} \cdot \mathbf{B} = -g_L \frac{e}{2m_e} J_z B = -g_L \mu_B m_j B \tag{8}$$

Note that when S = 0, J = L and $g_L = 1$ so that Eq. (8) reduces to Eq. (3) resulting in only 3 spectral line as expected from the Zeeman-Lorentz model. On the other hand, when L = 0, J = S we have again 3 lines but this time with the "wrong" B dependence as $g_L = 2$. For other values of S and L, g_L takes intermediate values.

If the transition is between levels with the same m_j then the photon's energy is unshifted by the magnetic field. But if the change in m_j is ±1, then the Zeeman shift in photon energy is

$$\Delta h\nu = (g_L m_j - g'_L m'_j)\mu_B B = g_{eff}\mu_B B \tag{8}$$

where $\Delta m = m_j - m'_j = \pm 1$, g'_L and g_L are the Lande' g-factors for the upper and lower levels respectively and g_{eff} is the effective g-factor for the transition. In the case $g_L = g'_L = 1$ the resulting spectrum is the same as that in Fig. 1, corresponding to the "normal" Zeeman effect. Note that you will get a three line pattern as long as $g_L = g'_L$. If $g_L \neq g'_L$ you will observe more than three lines in the spectrum also known as the anomalous Zeeman effect.

Atoms with many electrons. For atoms with many electrons the Zeeman effect is more complicated. The motion of the electrons in an atom is governed by: (a) the electrostatic forces of attraction between the nucleus and electrons and of repulsion between pairs of individual electrons; (b) the magnetic forces due to orbital motions and the spins of the electrons. These interactions are complex but for particular configurations one may make simplifying

assumptions in order to perform calculations. The assumptions specify a model for the system and different models will require different notations which specify the various angular momenta. Here we will focus on the simplest and most common model known as LS or Russell-Saunders coupling.

LS coupling arises from the predominance of electrostatic over magnetic interactions. In this model, the spins of the electrons are strongly coupled together to give a resultant $\mathbf{S} = \sum_i \mathbf{s}_i$

while their interaction with the orbital angular momenta are much weaker. The origin of the strong interaction which couples the spins is the electrostatic repulsion between the electrons due to the Pauli exclusion principle. In this model the orbital motions of the two electrons couple together also because of electrostatic interaction. The orbital motions are described by the orbital angular momenta so we may say that the orbital angular momenta couple together to give a resultant orbital angular momentum $\mathbf{L} = \sum_i \mathbf{l}_i$. Finally, $\mathbf{L}$ and $\mathbf{S}$ couple to form the

total angular momentum $\mathbf{J} = \mathbf{L} + \mathbf{S}$. The LS notation is given by $^{2S+1}L_J$.

Because the relative orientations of the vectors representing the individual electron's momenta can assume a variety of arrangements, the magnitudes of $\mathbf{L}$ and $\mathbf{S}$ can generally take on several values. For example, two electrons, both in states with $l=1$ may have a total, combined orbital angular momentum quantum number of L=0, 1 or 2 (see rules for angular momentum addition defined above). Their total spin angular momentum quantum number may be either S=1 or 0. Using the rule for addition of angular momenta the possible values of the total angular momentum J are summarized below:

	L=0	L=1	L=2
S=0	J=0	J=1	J=2
S=1	J=1	J=0, 1, or 2	J=1,2,or 3

We note that a given total angular momentum J, say J=1 might be obtained from 4 different combinations of L and S.   In general, we should expect that the two-electron atomic state would arise from some coherent superposition (mixture) of these different orthogonal eigenstates with the same total J. This is because the total angular momentum of the atom is conserved (constant of motion) in the absence of external torques, but the angular momentum of individual electrons is not.

It may turn out, though, that a given J arises in a particular multi-electron atomic state from a single, pure state that has a unique set of quantum numbers J, L, S. In this case the multi-electron state is an eigenstate of both $\mathbf{L}^2$ and $\mathbf{S}^2$ as well as of $\mathbf{J}^2$ (rather than a coherent superposition of several such states).

In this special case, which is valid for the Mercury and Neon lines studied here, the magnetic moment of the atom is the same as that in equation 5 except that J, L and S now correspond to the total angular momentum of all the electrons in the atom. Similarly the Zeeman shift is given by equation 8.

We note that the angular momentum of filled shells (all states with the same *n* are filled) or sub-shells (all states with the same *nl* are filled) add up to zero: S=L=J=0. As a result only electrons that are in partially filled shells – valence electrons - contribute to the atomic magnetic moment. For example Mercury has 80 electrons, but only two outer shell electrons contribute to the magnetic moment.

Selection rules and polarization of emitted photons (supplementary reading: "selection rules and polarization"). The transition between the Zeeman shifted states must obey conservation laws that determine which transitions can occur ("allowed") and which can't ("forbidden"). The allowed transitions are specified by the set of selection rules:

$$\Delta L = 0, \pm 1; \quad \Delta S = 0; \quad \Delta J = 0, \pm 1; \quad \Delta m_j = 0, \pm 1 \tag{9}$$

Photons emitted in a transition where $\Delta m = \pm 1$ are labeled σ lines and are circularly polarized when observed parallel to the magnetic field and linearly polarized perpendicular to the field when viewed at right angles to the field. Photons emitted in a transition with $\Delta m = 0$ are labeled π lines and plane polarized with the direction of polarization parallel to the field. When an atom undergoes a π transition, its angular momentum about the z-axis does not change. The atom satisfies this requirement by having its optically active electron oscillate along the z-axis, thereby giving rise to an electric field polarized in this direction. On the other hand, when the atom undergoes a σ transition, its optically active electron performs rotary motion in the x-y plane in order that the photon emitted carry angular momentum about the z-axis. The electric field then lies predominately in the x-y plane. Seen edge on, this constitutes a linear polarization perpendicular to the z-axis. Using a linear polarizer then one can separate these two types of transitions. When the light is observed perpendicular to the field the π and σ radiation will have the polarizations shown in the sketch in Fig. 2b. Fowles [reference 5] gives an excellent theoretical explanation for this polarization behavior (see especially Figs. 8-10 and 8-11).
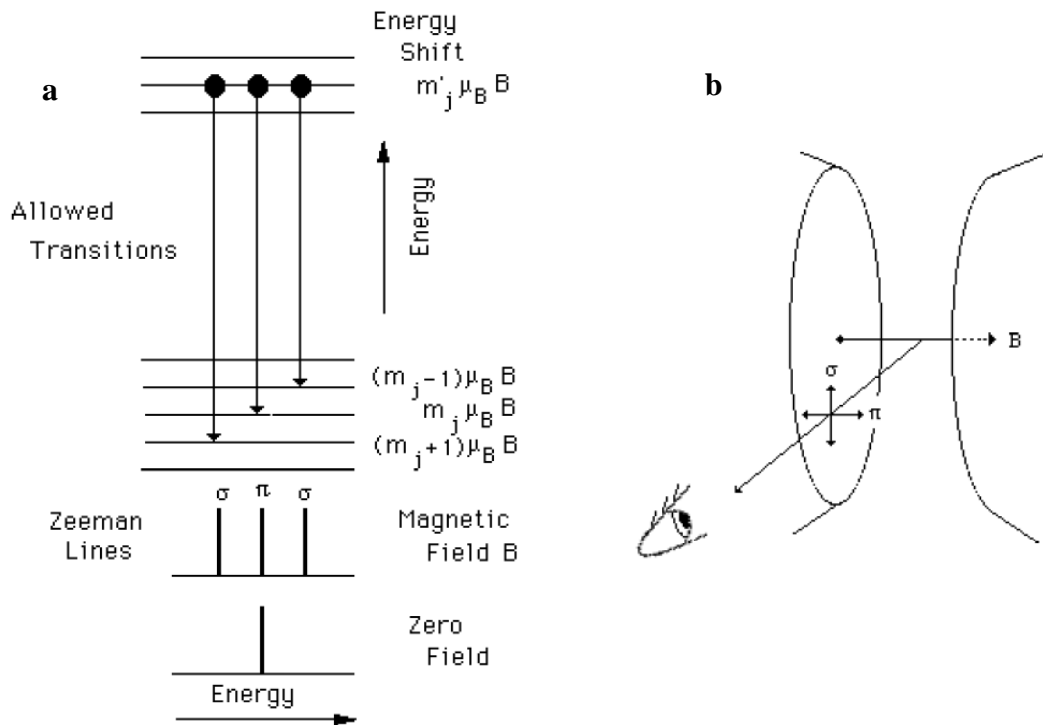

Figure 2. (a) Optical spectrum for $g_L = g'_L = 1$, the "normal" Zeeman Effect.
(b) Observing the polarization of π and σ radiation for the Zeeman Effect.

The Zeeman Effect in Mercury:

The mercury atom has 80 electrons and in the ground state these have the distribution:

shell	subshell	# of electrons
n=1	l=0	2
n=2	l=0, 1	8
n=3	l=0,1,2	18
n=4	l=0,1,2,3	32
n=5	l=0	2
	l=1	6
	l=2	10
	l=3	empty
	l=4	empty
n=6	l=0	2

The excited states have one electron lifted from the n=6, l=0 subshell and are shown in Figure 3 where the levels are labelled by the values of S, L, and J of the total atom according to the LS coupling notation. The full shells and subshells have zero contributions and so the net S, L, and J are due to one electron left in the n = 6, l=0 subshell and to the excited electron.

The ground state in mercury is then $^1S_0$.

The notation sometimes includes the n and l of the excited electron. For example:

• 7s $^3S_1$ has the excited electron with n = 7, l=0 with the totals S = 1, L=0, J=1

Notice that most transitions have no change in S. The levels with S = 0 are called singlets (no spin-orbit splitting) and the levels with S = 1 are called triplets (spin-orbit interactions give 3 close levels).

As shown in Fig. 3, the next levels above the ground state in mercury are a triplet of levels $^3P_0$, $^3P_1$, and $^3P_2$, corresponding to single electron states (6s6p) where the electron spins are parallel. There is a higher singlet $^1P_1$ state with spins antiparallel and still higher a 6s7s state. In the Franck-Hertz experiment you study transitions between the ground state and the $^3P_1$, which involves ultraviolet energies. The visible light you see coming from a discharge tube arises from an electron excited to the 7s state dropping down to a 6p state. Figure 3 shows the three most intense visible spectral lines.

To calculate the Zeeman spectrum of, for example, the blue line (435.8 nm) we first use Eq. (7) to calculate the Lande' g-factor for the $^3S_1$ and $^3P_1$ states:

$^3S_1$: J=1, L=0, and S=1 $\Rightarrow g'_L = 2$ (as expected for a pure spin state)

$^3P_1$: J=1, L=1, and S=1 $\Rightarrow g_L = 3/2$.

Then Eq. (8) tells us that the spectral line at $h\nu_0$ corresponding to the wavelength $\lambda = 435.8$ nm will be split into several lines by:

$$\Delta h\nu = g_{eff}\mu_B B = (\frac{3m_j}{2} - 2m'_j)\mu_B B,$$

where $m_j = 0,\pm1$, $m'_j = 0,\pm1$, and $\Delta m = m_j - m'_j = 0,\pm1$. Table 1 lists all possibilities.

The 435.8 nm line is split into seven lines as shown in Fig 4. However, as discussed in the next section, if the spectrum is measured without adequate spectrometer resolution the pattern may appear as a three-line spectrum whose lines broaden in width as well as shift position as the field increases.
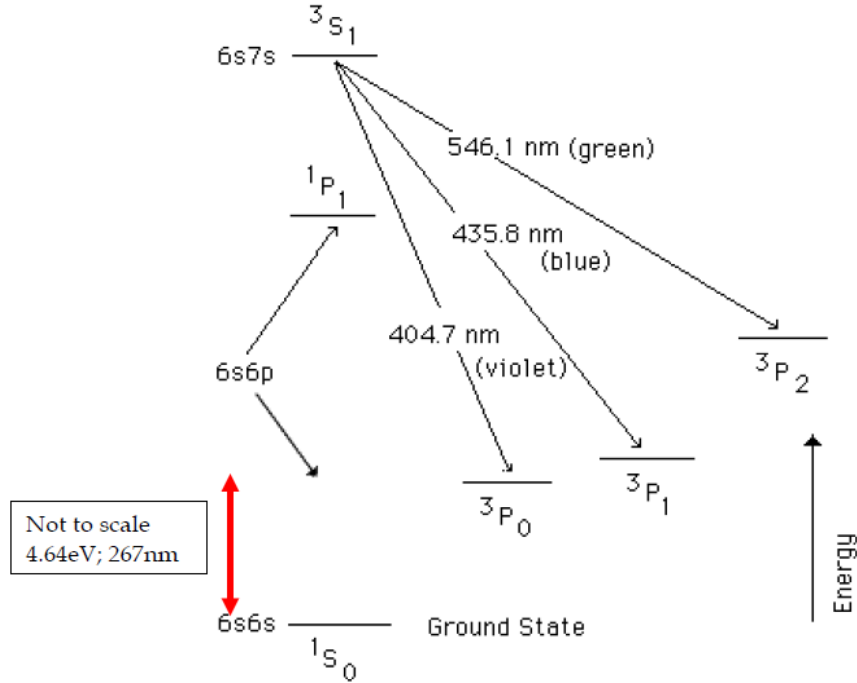
Figure 3: Energy Levels of Atomic Mercury

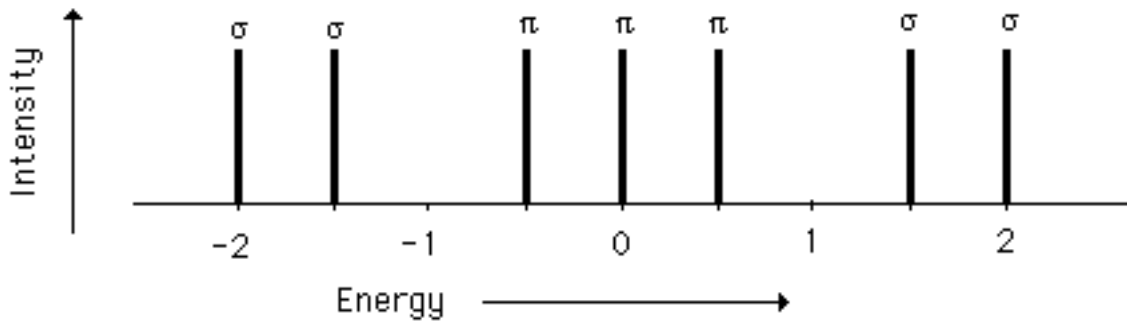| Table 1: Allowed Transitions 7s6s $^3S_1$ to 6p6s $^3P_1$				
m'_j	m_j	$\Delta\mu$	polarization	$g_{eff} = \Delta h\nu / \mu_B B$
1	1	0	π	-1/2
0	1	1	σ	3/2
-1	1	2		
1	0	-1	σ	-2
0	0	0	π	0
-1	0	1	σ	2
1	-1	-2		
0	-1	-1	σ	-3/2
-1	-1	0	π	1/2

Figure 4. Zeeman splitting of the 7s6s $^3S_1$ to 6p6s $^3P_1$ transition (in units of $\mu_B B$).

Similar calculations for the 7s6s $^3S_1 \mapsto$ p6s $^3P_2$ transition show a nine line pattern, while the 7s6s $^3S_1 \mapsto$ 6p6s $^3P_0$ transition shows a triplet that might be interpreted as the "normal" Zeeman effect except the splitting varies as $\pm 2\mu_B B$, while one would expect it to vary as $\pm \mu_B B$ for the "normal" effect ($g_L = g'_L = 1$).

Zeeman Effect in Neon
In the ground state Neon's 10 electron completely fill the n=1 and n=2 shells $1s^2, 2s^2, 2p^6$, so that S=L=J=0 and the LS notation is $^1S_0$.

When one of the electrons is excited, the electron configuration is $1s^2, 2s^2, 2p^5$ + "excited electron" or for short, $2p^5$ + "excited electron", or "parent ion" + "excited electron". The transitions to be studied in neon are between initial states with one electron excited to a 3P level and final states with one electron excited to a 3S level (not transitions to the ground state). These transitions are simple to study theoretically, because the neon atom can then be treated as a pair of particles — a hole in the n = 2 shell and an electron in the n = 3 shell. In this manner, all 9 unexcited electrons are treated as a single particle, a hole. If we label the excited electron as particle 1 and the hole as particle 2, the upper level for the transitions has $l_1 = 1$, $s_1 = 1/2$, $l_2 = 1$, and $s_2 = 1/2$. The lower level for the transitions has $l_1 = 0$, $s_1 = 1/2$, $l_2 = 1$, and $s_2 = 1/2$.

The strong orange line at 585.3 nm that you will study corresponds to the transition $1s^2 2s^2 3p^1 \rightarrow 1s^2 2s^2 3s^1$ or in LS notation: $^1S_0 \rightarrow ^1P_1$ as shown in Figure 5. For this case in turns out that both initial and final states are almost pure states so that the L-S coupling which is assumed in the derivation of the Lande' g-factor of Eq. (7) is a fairly good approximation.

Effect of instrument resolution: There are several factors that determine the intrinsic width of the spectral lines such as the lifetime of the excited state, the Doppler shift due to the atomic motion and the effect of collisions within the discharge tube (see discussion in Melissinos reference 1. Also https://en.wikipedia.org/wiki/Spectral_line_shape). But with the apparatus available in our laboratory the observed linewidth is determined by the resolution of the spectrometer. This resolution is determined by factors such as the number of grooves per mm in the diffraction grating and the width of the entrance and exit slits. The spectrometer you will be using has a resolution of 0.06 Å = 0.006 nm, where the resolution is defined to be the full width of the spectral line at the point where its intensity drops to one-half of its peak value. To understand the effect of instrumental resolution, we calculate the wavelength splitting for a Zeeman energy of $\Delta h\nu = g_{eff}\mu_B B$. Using $\lambda\nu = c$, where c is the speed of light, we find

$$|\Delta\lambda| = \frac{\lambda^2}{c}\Delta\nu. \tag{9}$$

Thus

$$|\Delta\lambda| = g_{eff}\frac{\lambda^2}{hc}\mu_B B = 4.668 \times 10^{-8} g_{eff}\lambda^2 B \tag{10}$$

where wavelengths are in nm and B is in Tesla. The maximum value of B that you will be

able to produce in the lab is about 1 T. So for the 435.8 nm 7s6s $^3S_1$ to 6p6s $^3P_1$ transition we find $|\Delta\lambda| = 0.0089 g_{eff}$ nm which is only moderately larger than the resolution. Figure 5 shows a simulation of the spectrum corresponding to the σ components of the 7s6s $^3S_1$ to 6p6s $^3P_1$ transition. In the figure the intensity of the σ four components given in Table 1 (g_{eff} = -2, -3/2, +3/2, and 2) are added assuming a Lorentzian line shape for the individual lines:

$$I(\lambda) = \frac{1}{\pi\delta\lambda} \frac{1}{1+\frac{(\lambda-\lambda_o)^2}{\delta\lambda^2}} \qquad (11)$$

$^3P_1$

where λ_o is the wavelength of the unsplit line and $\delta\lambda$ is the width caused by instrumental resolution (the resolution equals $2\delta\lambda$). [The factor $\pi\delta\lambda$ normalizes the intensity so that $\int_{-\infty}^{\infty} I(\lambda)d\lambda = 1$.] The simulation shows that the resolution will not be good enough to resolve the predicted four line σ pattern for the available magnetic field. Note that the peak intensity drops by a factor of more than three and the line width increases, which will affect the signal-to-noise. Also note that the unresolved peak of the two lines falls between their splitting for $g_{eff} = 2$ and $g_{eff} = 3/2$. Thus the measured effective g-factor should fall at about 1.75 and you will be able to clearly recognize that this is an example of anomalous Zeeman effect even though you will not be able to resolve the predicted spectrum. Likewise the π lines will not be resolved, but you should observe the line to broaden as the magnetic field is increased. In contrast the pattern for the 7s6s $^3S_1$ to 6p6s $^3P_0$ transition, which involves only two σ lines will be fully resolved and should agree with the theoretical prediction, $g_{eff} = 2$.
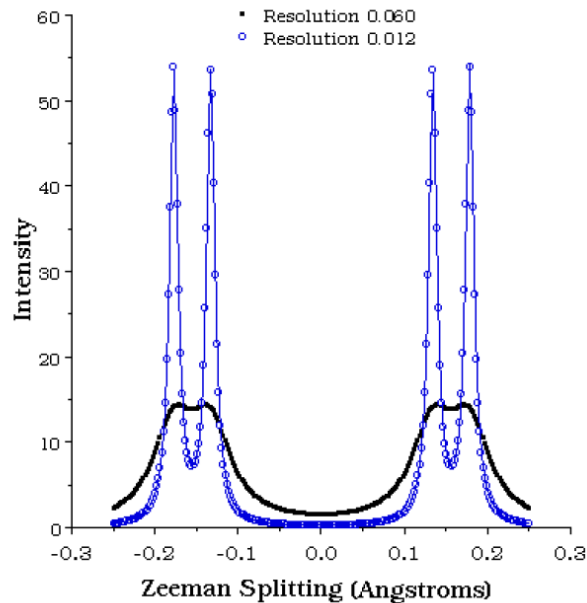

Figure 5. Dependence upon spectrometer resolution of the predicted Zeeman spectrum of the 7s6s $^3S_1$ to 6p6s $^3P_1$ transition in mercury B= 1 Tesla (σ polarization)

APPARATUS: Spex 1000M 1 meter grating spectrometer system including: 1800 lines/mm holographic grating, "Quickscan" thermoelectrically cooled linear diode detector array, Hamamatsu R928P side-window photomultiplier photon detector w/ high voltage supply and preamplifier-amplifier, Jabon Yvon-Spex "Spectramax" control and data acquisition software and Dell 486 computer; Hg and Ne discharge tubes; Gas discharge power supply; Penray miniature Hg discharge tube and power supply; Iron core electromagnet, Varian 6121 30-ampere Variac magnet power supply; RFL Industries model 904 Gaussmeter with Hall probe; Fiber optic feed/collimator with rotatable polarizer.

Safety: Beware of the high voltage on gas discharge tube power supply. It can give you a painful shock. Also, to avoid overheating the magnet coils, do not run the electromagnet above 5 amperes for more than 20 minutes. [Occasionally feel the coils. If they feel very warm, turn off the magnet and let them cool for 30 minutes.]

The Spex 1000M is a **Czerny-Turner scanning spectrometer** that uses a holographic 1800 groves/cm diffraction grating to disperse incoming light by wavelength into a spectrum. The direction of incidence of the light and the direction of observation, Fig. 6, are both fixed. Incident light containing a mixture of wavelengths passes through the entrance slit and strikes the first (collimating) mirror which makes the rays parallel and directs them toward the grating. The grating disperses the light over a range of angles depending on the wavelength. Rays of a specific wavelength, which depends on the angle between the grating and the incoming rays, travel to the second mirror and are refocused through the exit slit onto the detector. The spectrum is scanned by rotating the grating to sweep light of a particular wavelength onto the detector.
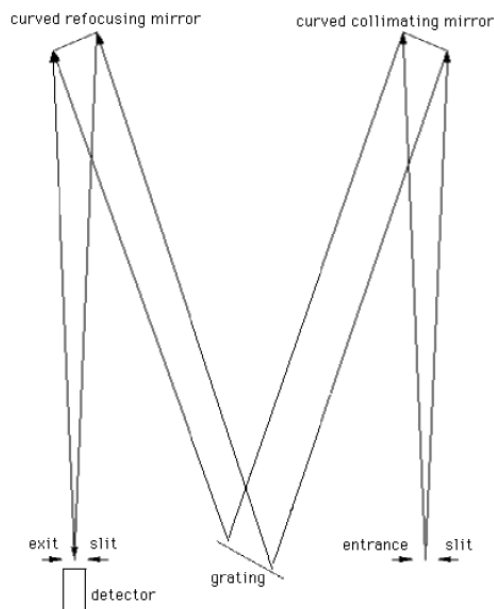

Figure 6. Czerny-Turner Scanning Spectrometer

The spectrometer has two detectors. If the dispersed light is allowed to pass through the

exit slit as shown in Fig., then it strikes a linear array of 1024 detectors (each one micron wide). The array allows you to simultaneously observe the spectrum over a range of wavelengths, which greatly increases the speed of data taking but at the expense of lower efficiency.

There is a mirror that can be swung into the exiting beam to divert the rays toward a photomultiplier photon detector on the side of the instrument. The phototube can measure only one wavelength at a time but has much lower background noise and is more useful for precision or for low light intensities.

The width of the entrance slits can be individually adjusted using the dial knobs at the entrance and exit ports of the machine. The wider the slits the more light reaches the detector, but on the other hand the resolution is improved by narrowing the slits. Widths of $10\,\mu m$ generally give good results : coarse setting to 0 and find setting to ~ 20. You should use the same setting for the entrance and exit slits. The slit settings would usually be at the correct values if previous runs gave good results.

The entire apparatus is computer controlled. A stepper motor rotates the mirror the grating in adjustable steps (e.g. 0.005 nm/step). The dwell (integration) time at each wavelength is also adjustable (e.g. 2 s/step). During this time the photomultiplier output is integrated (averaged) to improve signal-to-noise. Data analysis options are available for determining peak areas, channel counts, peak wavelengths etc.

The **electromagnet** consists of a soft iron core which taper to a small (~ 1 cm) gap.   The core is wound with two coils which generate a field in the gap of about 1.5 T when a current of 10 amperes (max) is applied to the coils. Care must be taken not to overheat the coils which should be allowed to cool whenever they feel moderately warm to the touch.

The magnetic field is measured with a **calibrated Hall probe**. Because of the iron core, the magnet exhibits hysteresis and you cannot count on a given current producing a specific field. You will need to establish a hysteresis curve as described in appendix 1. When inserting the Hall probe in the gap be sure to place it at the very center of the gap with the face of the probe parallel to the gap faces!

To measure a spectrum a discharge tube is placed in the gap. Its light is collected from the portion of the tube in the very center of the gap and is transferred to the spectrometer with a fiber optic feed. A **Polaroid filter** is mounted in the front end of the fiber optic. The orientation of the filter is read from the graduated wheel: 24° corresponds to polarization perpendicular to the field and 114° to parallel.

PROCEDURE: Before starting the experiment:
1.   Calculate the predicted Zeeman splitting of the 7s6s $^3S_1$ to 6p6s $^3P_0$ transition in mercury -- i.e. calculate g_{eff}. Include this calculation in your final report.
2. Establish the hysteresis curve for the magnet (see appendix 1).

3. Turn on the spectrometer SPEX MSD 2 and the Horiba high voltage power supply. Turn

on the computer and start the acquisition program (SynerJY). Familiarize yourself with the program functions by going to HELP.

SPEX MSD2 spectrometer and Horiba data acquisition module.

To set up data collection click on the icon that looks like a graph (bottom row, first icon on the left). See example in the figure below for taking the spectrum of the 404.7 Hg line. Set the desired parameters and then click on the RUN icon at the bottom. The spectrometer will start sweeping and taking data. See an example of the result in the right panel. The range was 404.9 to 405.3, averaging time 0.5s, step size 0.0005. Apertures on the spectrometer were both set at 20 for this data.
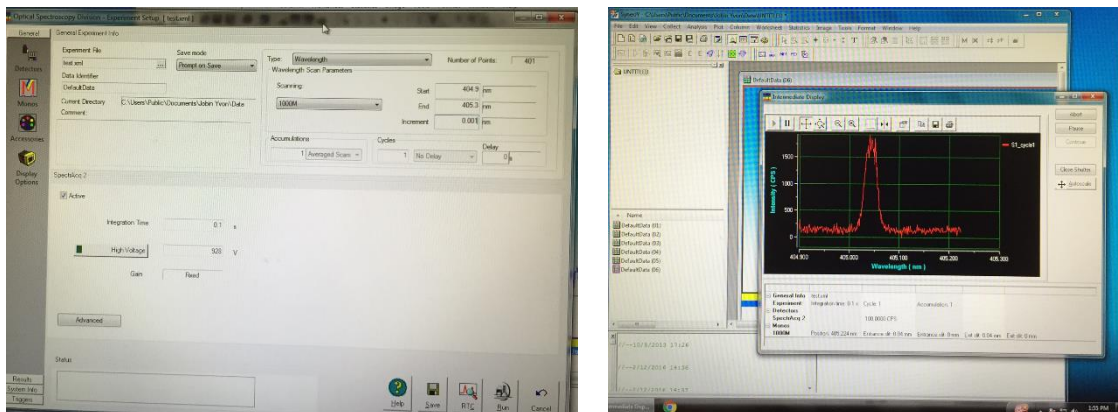
Example of Data acquisition with the SynerJY program.

4. Ask TA to help you insert the Penray miniature Hg discharge tube into the magnet gap and center the tube. Carefully center the collimating tube for the fiber optic feed and polarizer on the portion of the Hg tube that is in the center of the magnet gap. Set the Polaroid to 114°. Connect the discharge tube to its power source (Cenco high voltage transformer), with a rheostat in series with the primary. (Be sure the supply is switched off.) Start the discharge in the tube. (Always be careful of the high voltage).

Record the spectrum of the 404.7 nm mercury line. Use a narrow sweep range with long integration time so that the line is spread out with good signal-to-noise. Scan at several wavelength step sizes, integration times and sweep ranges to familiarize yourself with the effect of these parameters on the signal to noise and peak shape. Measure the line width (full width at half maximum intensity) to determine the resolution of the spectrometer. [There will be a residual field of about 0.03 T in the gap, which will produce a small

Zeeman splitting. But by setting the Polaroid to parallel polarization, you are eliminating the σ lines and any Zeeman broadening they might contribute to the line.] Practice recording peak wavelengths and peak areas (counts <u>per second</u> x Å calculated by acquisition program from counts and accumulation time - not counts) and background levels.

Warning: The quartz glass permits ultraviolet lines to pass. Do not look directly into the lamp.

5. Turn on the magnet and increase the current to 10 amperes. Measure the σ and π spectra (figure out the optimal polaroid settings for each of the two spectra) of the 404.7 nm line. For the σ line repeat the measurement for lower values of the current corresponding to the desired magnetic field intensity calculated from your calibration curve and taking care to maintain the hysteresis curve you have established. [**Pay attention to the temperature of the magnet coils and let them cool if they become very warm**.] You should have enough data points to allow you to plot the field dependence of the splitting and to calculate the values of g_{eff} from the slope.

6. Repeat the procedure in 5 for the σ and π spectra of the Hg 435.8 nm and 546.1 nm lines with a sufficient number of points to extract the corresponding g_{eff} values.

4. Ask TA to help you replace the Hg tube with the neon discharge tube in the magnet gap. Start the discharge in the neon tube and adjust the rheostat in series with the high voltage transformer to the maximum value which assures reliable starting and discharge operation. The discharge is affected by the applied magnetic field and you will need to adjust the rheostat so that the discharge is stable when the magnetic field power supply is turned up to 5 amperes.

There are a number of nearby lines in the Ne spectrum: 588.2 nm (5), 587.3 nm (5), 587.2 nm (4), 586.8 nm (3), 585.3 nm (10) , 582.9 nm (2), where the figures in parentheses are relative strengths. Measure the spectrum for the 585.3 nm line for zero magnetic field and for the σ and π polarizations when the magnet current is 5 amps. Repeat for a number of field values to obtain the value of g_{eff} from plotting the data.

IF TIME PERMITS (extra credit)
Hg spectrum. Set the spectrometer to observe the other prominent Hg lines. The lines at 546.1nm and 435. 8 nm should be easily visible with an integration time of 0.1 second (try and see). The line at 312.6 nm may be invisible at 0.1 second, but clear at 10 seconds; you may not be able to see the very strong line at 253.65nm, even at 100 seconds, due to the source tube-glass ultraviolet cutoff and decreasing grating reflectivity.

You should be able to see the 312.57nm line at 0.01 second integration time. However, you may still be unable to see the 253.65 nm "resonance" (ground state) line. The Handbook of Physics and Chemistry gives the following relative UV line intensities:

Wavelength (Å)   Relative Intensity

3131.84	320
3131.55	320
3125.67	400
2536.52	15,000

Alkali doublets in sodium
Observe the sodium D doublets, 5890 - 5896, as the lamp heats up. You will observe how the relative peaks of the two lines change. Set Trace Mode to Overlayed. Do not touch the mouse during scanning. Take 4 spectra sequentially that demonstrate the change in the relative peaks of the two lines.

Balmer transitions in hydrogen
Here accurate determination of wavelengths is paramount, for comparison with theory. Calculate the expected wavelengths for the first 5 or 6 Balmer transitions in hydrogen. Scan these lines at high resolution (e.g. 0.05 Å step size or less) using phototube detection (switch on the SPEX MSD 2 is set to PMT) .

REPORT guidelines:
1. Describe the theory of the Zeeman effect and discuss how it is tested in your experiment.
2. Describe the different instruments you used (spectrometer, magnet and Hall probe) and their physical principle of operation. Use your own schematic diagrams if necessary. Explain the origin of hysteresis in the magnet. Do not copy figures or procedures from the writeup.
3. Display the data in neat compact figures including captions and legends for each figure. Make sure to include error bars on both axis when relevant. All the relevant parameters (instrumental settings, field value etc)   should be stated in the caption or legend.
4. Analysis of the data should be presented in close proximity to the relevant figure.
5. Discuss your results, including remarks about whether they support the theory, resolution, accuracy, sources of errors, etc.

The three visible mercury spectral lines that you have studied represent examples of the anomalous Zeeman effect. In your report calculate the predicted Zeeman spectra for all three cases (Table 1 and Fig. 4 give the results for the blue line).
For a well resolved spectrum the linewidth must be smaller than the Zeeman splitting. Two factors enter into the linewidth: the natural spectral line width and the instrumental resolution. The natural linewidth has two contributions the natural broadening due to the uncertainty principle (which is negligible for the spectral lines studies here) and the Doppler broadening due to the distribution of velocities in the gas.
a. Calculate the broadening due to the distribution of velocities in the gas assuming the temperature of the discharge is 500 K. How does your result compare with the instrument resolution?
b. Using the value of the largest line broadening obtained in (a) calculate the minimum magnetic field needed to resolve the σ lines of the $^3S_1$ to $^3P_0$ and the $^3S_1$ to $^3P_1$ transitions. Repeat the calculation for the π lines of the $^3S_1$ to $^3P_1$ transition.

The $^3S_1$ to $^3P_0$ transition is least affected by resolution problems. Plot the Zeeman splitting versus B for the σ lines and make a linear fit to determine the experimental value of g_{eff} and your errors. Estimate your error and compare with the prediction. Discuss the sources of any discrepancy.

For the $^3S_1$ to $^3P_1$ transition compare your spectrum for the σ lines with a simulation similar to that in Fig. 5 (see note below). Determine g_{eff} for these lines and compare with the value predicted in the simulation. For the π line prepare a simulation similar to Fig. 5 and compare with your data.

Note: for an accurate simulation, you should use the relative transition strengths for each polarization shown in the figure below (these could be calculated from matrix elements in time independent perturbation theory).
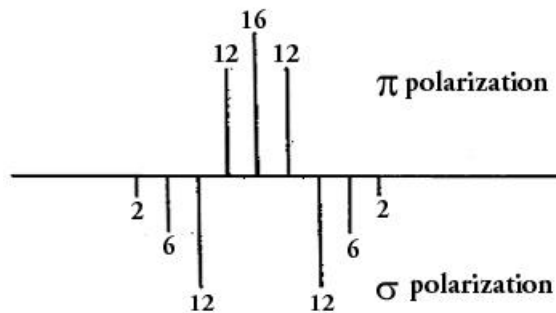
For the $^3S_1$ to $^3P_2$ **transition** compare your data with a superposed simulation of the predicted spectrum.

For the Neon $^1S_0$ to $^1P_1$ **transition** show the fit of your data for the Zeeman splitting versus field dependence and determine g_{eff} and errors. What can you say about the g-factors of the initial and final states?

Charge to mass ratio. Use the theoretical values of g_{eff} and the known value of Planck's constant to calculate the charge to mass ratio, e/m, of the electron from the measured Zeeman splitting data for the 404.7nm and 435.8 nm lines. Compare with the accepted value. Discuss possible origins of discrepancy.

REFERENCES:

1. A. Melissinos, Experiments in Modern Physics (AcademicPress, 2003).

2. McGraw hill Encyclopedia of Science and Technology, 7th ed, NY 1992, pp 615-617.

3 Halliday, Resnick, and Walker: <u>Fundamentals of Physics</u>, pp 791-792 (derviation of magnetic moment of a circular loop of current)

4 Serway, Moses and Moyer: <u>Modern Physics</u>, pp. 216-226 (normal and anomalous Zeeman effects) (theoretical discussion of Zeeman Effect)

5   G. R. Fowles: <u>Introduction to Modern Optics</u>, p. 247,Figure 8.11 (discussion of polarization characteristics of the Zeeman spectrum)

6   Supplementary reading on course website.

7   https://www.nist.gov/pml/atomic-spectra-database

APPENDIX 1: Establishing *the hysteresis curve* Do not leave the magnet current on for long periods of time above 5 amperes. The magnet will get hot.

Turn on the magnet power supply (be sure to set the output to zero!). Turn on the gaussmeter and calibrate it, following the instructions on top of the instrument

Remove any residual magnetism in the Zeeman magnet ("degauss") as follows: Raise the current to +9 amperes (which current direction is + is arbitrary) and back to zero, switch off the power supply and <u>reverse polarity</u>; raise current to -8 amperes and back to zero, switch off and reverse polarity; raise current to +7 amperes and back to zero, switch off and reverse polarity, etc. Continue until you reach 1/2 ampere.

Hereafter you will maintain a definite magnetic hysteresis curve by always increasing the current up to 8 amperes in the same sense, and by always decreasing the current back down to zero before raising it again. Turn current down to zero (from 8 amperes)before switching off-do not switch off with current flowing. This is good practice with any magnetic circuit, to avoid inductively generated high voltages and possible arcing. Cycle a few times between 0 and 8 amperes (no polarity reversals) to establish your hysteresis loop before beginning observations of Zeeman splitting.