# PHYSICS LABORATORY

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Thermodynamics and Modern Physics

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Atul Singh Arora: *Physics Laboratory*, Thermodynamics and Modern Physics,

*Every honest researcher I know admits he's just a professional amateur. He's doing whatever he's doing for the first time. That makes him an amateur. He has sense enough to know that he's going to have a lot of trouble, so that makes him a professional.*

*— Charles F. Kettering (1876-1958) (Holder of 186 patents)*

# ACKNOWLEDGEMENTS

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# ACRONYMS

# 1 CHARGE TO MASS RATIOE/M

January 8 and 15, 2012

## 1.1 AIM

To determine the charge to mass ratio (e/m) of an electron by the helical method (long solenoid).

## 1.2 APPARATUS

e/m by Helical Method apparatus (we used the one by SIBA India), connecting wires

## 1.3 CATHODE ANODE

Cathodes are defined to be where a reduction takes place (chemically). Thus in accordance with the image appended, the anode is where the conventional current starts from and moves towards the cathode. For an electron, it starts from the cathode and moves towards the anode.

## 1.4 THEORY

Our objective here, as described earlier, is to determine the charge to mass ratio. For this, we shall describe here, an apparatus, without developing a motivation for doing the same. The setup for the apparatus is given in Figure 1.

First, consider a vacuum tube; in one edge, say the starting edge (there's a screen at the other edge), we place a cathode and a perforated anode and apply a constant potential difference between them (the polarity is implied from the definition of cathode), such that the electrons move away from the starting edge. Now we can evaluate the speed of the electrons that pass through the anode by invoking the work energy theorem as follows:

$$\frac{1}{2}mv^2 = eV \tag{1}$$

where the symbols have their usual meaning, viz. $m$ is mass of electron, $v$ is speed of electron at the instant described, $V$ is the potential applied across the anode and cathode, and $e$ is the charge of one electron. Refer to the diagram for direction conventions assumed. If we try to turn on the apparatus at this stage, we should just see a spot, we assume to be the centre of the screen (this may not necessarily happen experimentally, but can be adjusted; however for simplicity, we will discuss that later)

Now the next step is introducing a differential velocity component (do not confuse this with infinitesimal) along the X direction. This is done by applying an alternating electric field as shown in the figure. When the electrons reach the plane A, they would have a certain distribution of velocity components along the X direction. It is important to realize here that the distribution of electrons along the X axis will be fairly small, because the velocities are not large enough to cause enough spatial deviation, in the small time corresponding to the length of the accelerating plates. This condition can be achieved by making the speed of the electrons sufficiently large with respect to the length of the alternating electric field plates. Yet, when observed on the screen, a line would be obtained (it's length would depend on the strength of the alternating electric field) as the electrons get displaced along (or against) the X axis, as they're displaced by $L'$ along the Z axis, because of the initial velocity.

With that said, it is now that we introduce a uniform magnetic field B along the Z axis. We are certainly introducing certain errors by doing so, as the magnetic field in the experiment is present everywhere in the tube, when it's turned on. However, to simplify, we account for it's effect after the electrons have passed the plane A. Now most electrons would have a non-zero velocity component along the X axis, viz. a direction perpendicular to the uniform magnetic field. Thus, we can evaluate the radius of the acceleration of the electron with velocity $v_x$ can be evaluated as

$$\frac{m_e v_x^2}{r} = e v_x B \tag{2}$$

$$\Rightarrow \omega = \frac{v_x}{r} = \frac{m_e B}{m} = \frac{2\pi}{T} \tag{3}$$

$$\Rightarrow T = \frac{2\pi}{eB} \tag{4}$$

Using the formula for a solenoid and taking $\theta_1 = \theta_2 = \theta$ tending to zero in the following

$$B = \mu_0 NI(\cos\theta_1 - \cos\theta_2)/2L \tag{5}$$

where the symbols have their usual meanings and $\theta$ is the corresponding angle (loosely speaking, s.t. for the angle tending to zero, it results in an ideal, infinite length solenoid)

Using this and equating T to the time $t = l/v_z$ (time taken by the electron to travel the distance l, as given in the diagram), we get the following working formula.

$$\frac{e}{m} = \frac{V}{2I^2}\left(\frac{4\pi L}{\mu_0 N l \cos\theta}\right)^2 \tag{6}$$

where for our setup, we have $N = 980$ (the number of turns), $L = 43$ cm, $l_x = 13.5$ cm, $l_y = 11$ cm.

## 1.5 OBSERVATIONS AND CALCULATIONS

Observations have been appended at the end of this experiment.

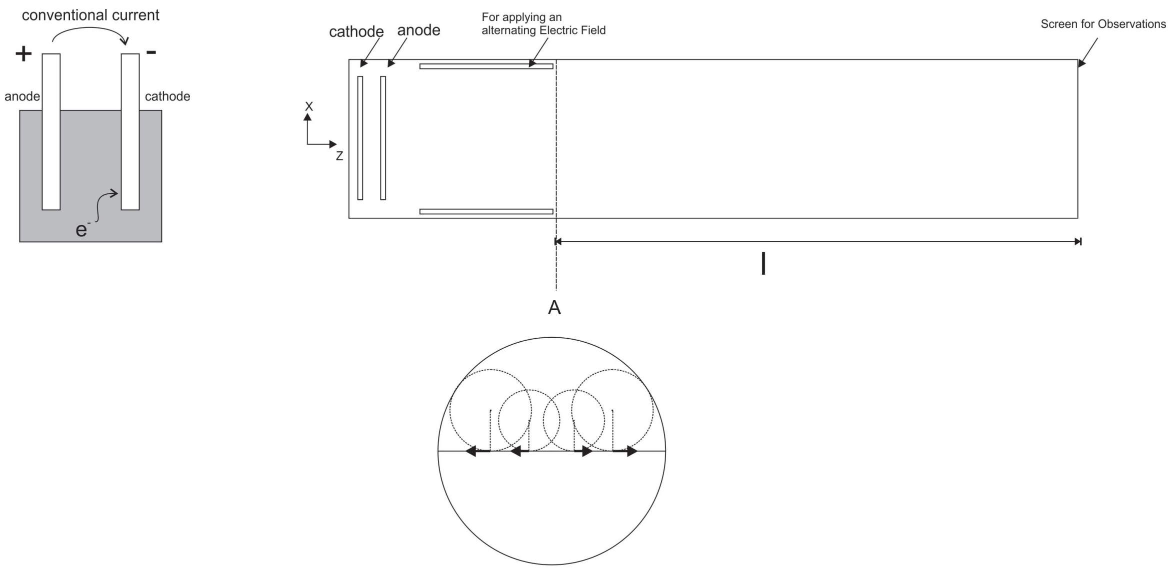


Figure 1: $\frac{e}{m}$ setup

## 1.6 PROCEDURE

1. Placed the solenoid in the wooden bracket such that its axis lies in the east-west direction (although this is not very important, since the magnetic field would change at most by about 2%). Mounted the CRT inside the solenoid at the centre. The power unit should be kept as far away as possible to avoid stray magnetic field. [1]
2. Connected the CRT with it's power-supply using the 8 wire plug into the octal base provided
3. Connected the solenoid with the DC power terminals colour-wise.
4. Turn off the magnetic field by using the corresponding knob.
5. Plug the supplies to the mains, and switch it on. Leave it for about three minutes for the CRT to warm up.

1 The procedure is highly influenced from the Lab Manual for PHY212, 2013

6. Adjust the accelerating voltage to get a spot. Adjust the focus and intensity to get a finer and clearer spot. Note the accelerating voltage.

7. Apply an AC voltage to the Y or X plates by means of the DEF volt control. Do note that you need to turn on the deflection plate to centre the position of the spot, while the DEF knob is at zero. Otherwise the control for centring doesn't work.

8. Now adjust the deflection to about 2 cm.

9. Now put the DC in the forward direction. Turn on the solenoid current and increase the DC voltage till the line reduces to a point. (you are increasing the magnetic field)

10. Reverse the DC voltage using the other knob and again find a DC voltage to get a point. Note both currents

11. Repeat the same with Y or X plates (depending on which you did first)

12. Use the formula derived earlier and plug in the value of the slope of the V vs $I^2$ graph.

## 1.7 RESULT

The expected $e/m$ ratio is $1.66 \times 10^{11}$ C/Kg. Experimentally, we obtained $(1.66 \pm 0.11) \times 10^{11}$ C/Kg and $(1.57 \pm 0.14) \times 10^{11}$ C/Kg for X (with a 7% standard error) and Y (with a 9% standard error) axis respectively.

## 1.8 PRECAUTIONS

Precautions have been embedded place-wise in the procedure.

# 2 FRANK HERTZ

February 16, 2013

## 2.1 AIM

To experimentally verify that atomic energy levels are discrete, using the frank-hertz setup.

## 2.2 APPARATUS

Frank Hertz Apparatus, An Oscilloscope, a few connecting wires and a camera or tracing paper

## 2.3 THEORY

### 2.3.1 *Rationale Behind the Experiment*

This experiment is very fascinating, for it experimentally, using a rather naive method, proves the atomic energy levels are discrete.

The basic idea is to bombard atoms with progressively higher energy electrons, and measure the current of these electrons. When the electrons have specific, discrete energy values, they collide plastically with the atoms and the current drops. If we plot the energy of the electrons against the current obtained, the difference in energy between two consecutive valleys (in the graph), will give the energy difference between two atomic states.

### 2.3.2 *Experimental Setup*

The detailed setup of the experiment is beyond the scope of this report. However, to a first approximation, the setup can be understood in terms of a triode as given in Figure 2. An electrode is heated by flow of electric current. This thermal energy, acquired by the electrons, if exceeds the binding energy of the electron with the metal, results in ejection of electrons from the metal surface. (Of course there would be a distribution of thermal energy, however, here we are not getting into the quantitative details) There's another electrode, called the grid, which is at a higher potential with respect to the cathode (the first electrode, which releases electrons). This potential is maintained to a desired value by a variable potential source. Most electrons, get through the grid, and gain an energy equivalent to $eV$ where $e$ is the charge of an electron, and $V$ is the potential difference between the electrodes. So far so good. Now we introduce a third electrode. The magnitude of potential difference between the grid and the cathode is greater than that between the grid and the third electrode (call it $V_2$), viz. $|V| > |V_2|$. Consequently, the current that flows through the third electrode, will be constituted by electrons that have an energy greater than $eV_2$. The entire setup is enclosed within a vacuum tube, with Argon atoms.

Now we vary $V$ to increase the maximum kinetic energy and measure the current I through the third electrode. The current is expected to increase in a known fashion (precise details are not relevant at the moment) in the absence of Argon. In the presence of Argon, the current drops periodically to a minima, at constant voltage differences.

## 2.4 OBSERVATIONS AND CALCULATIONS

Observations have been appended at the end of this experiment.

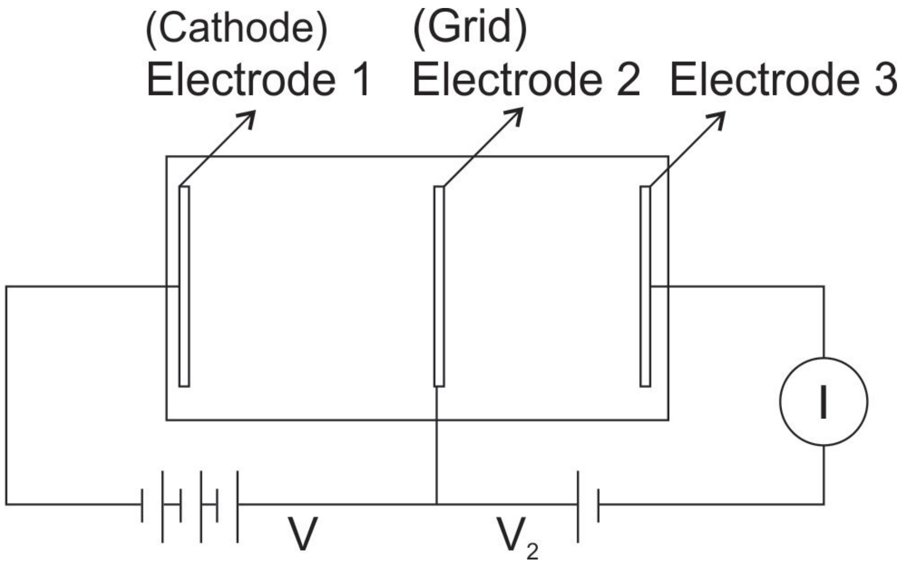


Figure 2: Simplified schematic of the Setup

## 2.5 ERROR ANALYSIS

Standard deviation in ‘difference’ was found to be $0.4eV$, for the manual mode.

The auto mode error was the least count error $= 1eV$

## 2.6 PROCEDURE

The procedure has been influenced heavily by the one given in the Physics Lab Manual, provided to us, during the course, PHY212, 2013.

1. Before switching on the power, it was made sure that the control knobs are at their minimum and the current multiplier knob is set to $10^{-7}$.
   a) Manual
   b) The Manual mode was selected using the Manual-Auto switch.
   c) Turned the display selector to $V_{G_1K}$ and adjusted the corresponding knob to read 1.5V on the display
   d) Next, $V_{G_2A}$ was selected and set to 7.5V
   e) Now, the $V_{G_2K}$ knob was turned and the variation of the current (these correspond to V and I discussed in the theory) noted, with increase in voltage from zero.
   f) The graph for the same is plot and average distance between two successive maxima (or minima) is calculated. This gives the first excitation potential for Argon.
   g) Automatic
   h) Scanning mode was selected by turning the Manual-Auto switch to auto.
   i) The instruments X, Y, G sockets were put in the corresponding sockets of the CRO.
   j) The scanning range switch of the CRO was set to X-Y mode/external X.
   k) Switched on the scanning knob of the instrument and the waveform observed.
   l) The X-gain and -gain were adjusted to obtain a clear waveform and the Y amplitude within the screen range.
   m) The horizontal distance was again measured between the peaks.

## 2.7 RESULT

The expected value of the first excitation energy of Argon is $11.83eV$. Experimentally, from the manual mode, the same was found out to be $11.7 \pm 0.4eV$, and from the auto mode, it was found out to be $12 \pm 1eV$. Figure 3 shows the graph corresponding to the manual mode.

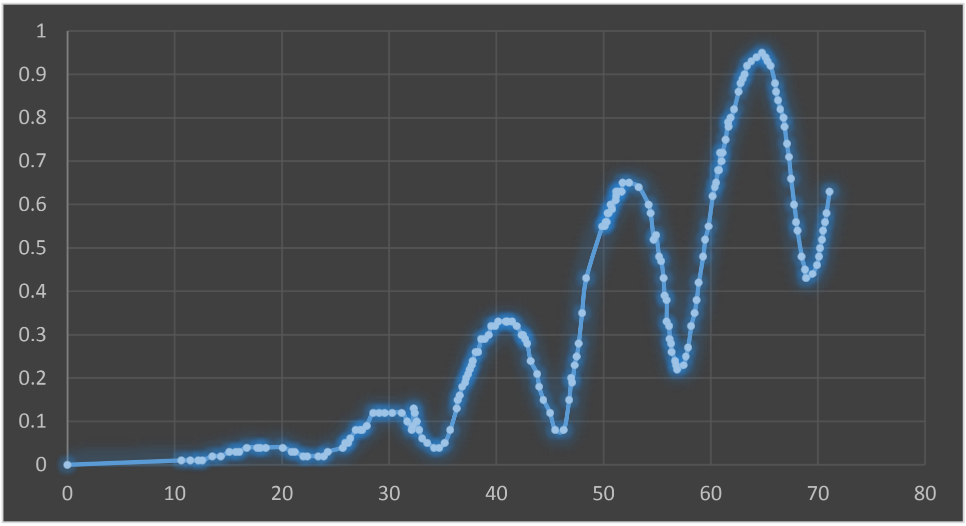


Figure 3: Graph for the Manual Mode

# 3 HYDROGEN BALMER SERIES AND RYDBERG CONSTANT

Feb 19 and 26, 2013

## 3.1 AIM

To experimentally measure the Balmer series line of the Hydrogen spectrum and calculate Rydberg's constant, R from the result.

## 3.2 APPARATUS

Hydrogen Discharge tube, Diffraction grating, Spectroscope

## 3.3 THEORY

### 3.3.1 *Motivation*

The Spectrum of hydrogen is spread over a large range in the electromagnetic spectrum. The visible part is known as the Balmer series, given by the formula

$$\frac{1}{\lambda} = R\left[\frac{1}{4} - \frac{1}{n^2}\right] \tag{7}$$

where n is an integer > 2. The general formula for the Hydrogen Spectra is given by

$$\frac{1}{\lambda} = R\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right] \tag{8}$$

where $n_f > n_i$. This reduces to the previous formula for $n_f = 2$. This equation was derived by Rydberg as a phenomenological description. The same equation was derived by Bohr, from more basic principles of physics, using quantization ideas from Plank and Einstein, and certain other bold assumptions (no radiation for specific orbits and angular momenta) to conclude the following

$$R = \frac{me^4}{8\epsilon_0^2 h^3 c} \tag{9}$$

where m and c are mass and charge of the electron

#### 3.3.2 *Experimental Setup*

The setup is fairly straight forward. We have a Hydrogen discharge tube (source of Hydrogen spectrum) placed in front of a [[telescope device]] with a diffraction grating in between. This grating results in splitting of the spectrum spatially. We measure the positions of these split lines to find their wavelengths and plot the corresponding quantities to find the value of R.

#### 3.3.3 *Useful Results*

To calculate $\lambda$, we use the relation $d \sin\theta = m\lambda$ with $m = 1$.

R in SI units is $1.09 \times 10^7 m^{-1}$

The wavelengths of the Balmer series are 656.28 nm, 486.13 nm, 434.05 nm and 410.17 nm, for $n = 3, 4, 5$, and 6 respectively.

### 3.4 OBSERVATIONS AND CALCULATIONS

Please refer to Figure 4. The Rydberg's constant was determined to be $1.00 \times 10^7$ with $R^2 = 0.9213$ for the straight line fit.

### 3.5 PROCEDURE

The procedure has been influenced heavily by the one given in the Physics Lab Manual, provided to us, during the course, PHY212, 2013.

1. Focussed the telescope to infinity (Took the telescope outside the dark room for this, focussed at something outside the window)

2. Placed the light source about 1 cm from the collimator slit. The slit was left barely open.

3. Looked through the eye piece and adjusted it to ensure the cross wire is aligned well and visible. Do NOT move the telescope's focus

4. Rotated the telescope arm to align directly with the collimator.

5. Turned on the light source and viewed the slit of the collimator

6. Focussed the collimator to obtain a sharp image of the slit.

7. Now placed the diffraction grating in the corresponding mount, at right angles to the axis formed by the collimator and the telescope

8. Looked straight through the telescope to continue seeing the direct image of the slit. Ensure at this stage that the image is getting formed at the centre.

9. Used the cross wire to measure the left and right edge of the slit

10. Rotated the arm of the telescope to left or right, and observed the coloured spectrum. The contrast of the lines can be increased at the cost of brightness by adjusting the slit width. This may be done to identify the first order lines. Higher order lines come at higher angular deviations.

11. Noted the position of the three Balmer lines corresponding to $n_i = 5, 4$ and 3.

## 3.6 RESULT

The expected value of the Rydberg constant $R = 1.09 \times 10^7 m^{-1}$. Experimentally this was determined to be $(1.00 \pm 0.078) \times 10^7$ ($R^2 = 0.9213$ for the straight line fit whose slope is the Rydberg's constant).

| | MSD (Left) | VSD(Left) | Angle (Left) | MSD (Right) | VSD (Right) | Angle (Right) | Corrected Angle | |
|---|---|---|---|---|---|---|---|---|
| **Left for centre** | 295.5 | 0 | 295.5 | 115.5 | 0 | 115.5 | 295.5 | |
| **Right for centre** | 295 | 59 | 295.0295 | 115 | 58 | 115.029 | 295.02925 | |
| **Mean for centre (calculated)** | | | | | | | 295.264625 | |
| **Blue (absolute)** | 309 | 0 | 309 | 129 | 0 | 129 | 309 | |
| **Red (absolute)** | 314.5 | 12 | 314.506 | 134.5 | 7 | 134.5035 | 314.50475 | * |
| **Green (absolute)** | 311.5 | 50 | 311.525 | 131.5 | 48 | 131.524 | 311.5245 | * |
| **Green II (absolute)** | 312 | 31 | 312.0155 | 131.5 | 48 | 131.524 | 311.76975 | * |

297 * The readings other than blue, were taken with respect to this

| | Corrected Angle | Wavelength in cm | Wavelength in nm | 1/lambda | (1/4 - 1/(n^2)) | Expected | Expected Angle |
|---|---|---|---|---|---|---|---|
| Blue | 13.735375 | 4.02062E-05 | 402.06 | 2487181 | 0.222222222 | 410 | 14.01205171 |
| Green | 14.5245 | 4.24678E-05 | 424.68 | 2354726 | | | |
| Green II | 14.76975 | 4.3169E-05 | 431.69 | 2316475 | 0.21 | 434 | 14.85058324 |
| Red | 17.50475 | 5.09329E-05 | 509.33 | 1963367 | 0.1875 | 486 | 16.67890632 |

| | | |
|---|---|---|
| **Lines per inch** | 15000 | |
| **Separation between lines** | 6.66667E-05 | inches |
| **d** | 0.000169333 | cm |

**Rydberg's Constant** 1.00E+07 ± 7.87E+05 1/m

R^2= 0.9213

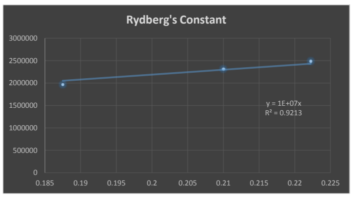


Figure 4: Observations for Frank-Hertz

# 4 QUINCKE'S METHOD

March 19 and 26, 2013

## 4.1 AIM

To determine the magnetic susceptibility of an $Mn^{2+}$.

## 4.2 APPARATUS

U-tube, $Mn^{2+}$ solution (to make the solution: Volumetric Flasks, foil paper, weighing balance), Magnetic Field Sensor, Magnetic Field Producer

## 4.3 THEORY

### 4.3.1 *The Rationale*

A spatially varied magnetic field can apply force on a magnetic moment. In this experiment, such a field is applied to one arm of a u-tube containing a paramagnetic liquid. The force is balanced by a height difference between levels of the liquid in the two arms.

Simple calculations reveal that the force depends only on the value of the magnetic field at the beginning and end of the spatial region (of presence of the magnetic field). These are readily measurable. Further, the said height difference can be measured easily using the setup provided. As will be derived, there's a relation between these quantities that may be used to yield the 'magnetic susceptibility' of the paramagnetic material, which is what we wish to investigate here. This quantifies how strongly the substance magnetizes in response to an external field.

### 4.3.2 *Derivations*

The experimental setup must be clear before continuing with this section. The conventions used will be defined as and when required.

#### 4.3.2.1 *Magnetization of bulk*

The magnetization $\mathbf{M}$ of a bulk material is defined as the magnetic dipole moment per unit volume. For a paramagnetic material, $\mathbf{M}$ is parallel to $\mathbf{B}$, the applied field and they're related as

$$\mathbf{M} = \frac{\chi \mathbf{B}}{\mu_0} \tag{10}$$

#### 4.3.2.2 *Force due to a Magnetic Field*

The following will not be derived, but used directly. Here $\mathbf{F}$ is the force, $\mathbf{m}$ is the magnetic moment, $\mathbf{B}$ is the magnetic field.

$$\mathbf{F} = \nabla(\mathbf{m}.\mathbf{B}) \tag{11}$$

Before proceeding, we specify here the direction conventions. The u-tube is parallel to the Y-X plane. The two open arms are along the X axis. Within the tube, the z-axis corresponds to the direction of the magnetic field (whose magnitude is a function of position).

Now, in our case, we'll use $\mathbf{M}$, instead of a single magnetic moment $\mathbf{m}$, which is the magnetic moment for a unit volume. However, since $\mathbf{M}$ is not expected to be constant over a given volume in general, we need to be a little more careful before substituting. Let the magnetic moment at some arbitrary height be given by $A\mathbf{M}dx$, where $A$ is the cross sectional area of the u-tube and $dx$ an infinitesimal height. [1] This is justified as the magnetic field for any given height is constant. So using Equation 10 we have

$$d\mathbf{m} = A\mathbf{M}dx = A\frac{\chi \mathbf{B}}{\mu_0}dx \tag{12}$$

Thus we can write Equation 11 as

$$\begin{aligned} d\mathbf{F} &= \frac{A\chi}{\mu_0} \qquad \nabla(B^2 dx) \\ &= \frac{A\chi}{\mu_0} \quad [\mathbf{x}\frac{\partial}{\partial x}(B_x^2 + B_y^2 + B_z^2)dx \\ &\qquad\quad \mathbf{y}\frac{\partial}{\partial y}(B_x^2 + B_y^2 + B_z^2)dx \\ &\qquad\quad \mathbf{z}\frac{\partial}{\partial z}(B_x^2 + B_y^2 + B_z^2)dx] \end{aligned} \tag{13}$$

Now in accordance with the experimental setup, only $B_z \neq 0$ and $B_z$ is invariant with respect to Y and Z co-ordinates (restricted to within the u-tube), we get

$$d\mathbf{F} = \mathbf{x}\frac{A\chi}{\mu_0}\frac{\partial B_z^2}{\partial x}dx \tag{14}$$

1 we are ignoring in the analysis the bottom most part of the tube

We now have an expression which just needs to be integrated to give the final result. However, there're two caveats. One is that for the same $x$, the term $dF$ can have at most two values depending on which arm we are looking at. [2] Second is that we must apply the limits very carefully. This upward force is exerted only at all points within the tube where $\frac{\partial B_z^2}{\partial x} \neq 0$. So if we integrate from the top of the first arm to the top of the second, say from $x_t, y_t$ to $x_b, y_b$, we'll have

$$\mathbf{F} = \mathbf{x}\frac{A\chi}{\mu_0}(B^2_{z(x_t,y_t)} - B^2_{z(x_b,y_b)}) \tag{15}$$

From this, we can readily calculate the pressure exerted by the magnetic field as

$$P = \frac{\chi}{\mu_0}(B^2_{z(x_t,y_t)} - B^2_{z(x_b,y_b)}) \tag{16}$$

Since at equilibrium, this must be balanced by some other force, the liquid in the arm subjected to the magnetic field rises to create a height difference, say $2h$, to balance the pressure, which by elementary analysis we know would be

$$P = \rho g 2h \tag{17}$$

This yields the final relation.

$$\chi(B^2_{z(x_t,y_t)} - B^2_{z(x_b,y_b)}) = 2\mu_0 \rho g h \tag{18}$$

#### 4.3.2.3 *Paramagnetic Susceptibility*

Water also has it's own susceptibility which contributes to $\chi$. So to evaluate $\chi_{Mn^{2+}}$, we have

$$\chi = \chi_{Mn^{2+}} + \chi_{\text{water}} \tag{19}$$

where $\chi_{\text{water}} = -0.9 \times 10^{-5} \frac{m^3}{kg}$. Further, $\chi$ here represents volume susceptibility. To get mass susceptibility, we, as is dimensionally obvious, have

$$\chi_m = \frac{\chi}{\rho} \tag{20}$$

## 4.4 OBSERVATIONS AND CALCULATIONS

Observations have been appended at the end of this experiment.

Slope of the graph equals $\chi/4\mu_0\rho g$ in $mm/G^2$.

For a 2M solution, the slope was $6 \times 10^{-9} mm/G^2$ with $R^2 = 0.992$ and for the 3M solution of was $6 \times 10^{-8} mm/G^2$ with $R^2 = 0.971$.

2 Observe that this still doesn't contradict the assumption that $B^2$ is independent of Y and Z coordinates *within* the u-tube

Now $\chi_{2M+water} = 4\mu_0\rho g(6 \times 10^{-4})$ in SI units, where $\rho$ = Molarity times molar mass + mass of water in one unit volume $= (338 + 1000)g/L = 1338kg/m^3$. On subsitution we get $\chi_{2M} = (1.054 \pm 0.008) \times 10^{-5} - 0.9 \times 10^{-5} = (1.54 \pm 0.08) \times 10^{-6}$.

Similarly, we have $\chi_{3M}$ (with $\rho = 1507kg/m^3$) = $(12.0 \pm 0.036) \times 10^{-5} - 0.9 \times 10^{-5} = (11.1 \pm 0.036) \times 10^{-5}$

## 4.5 ERROR ANALYSIS

$$\sigma(\text{slope}_{2M + \text{Water}}) = 0.048 \times 10^{-4} \tag{21}$$

$$\text{Thus error in } \chi_{2M + \text{Water}} = 4\mu_0\rho g(0.048 \times 10^{-4}) \tag{22}$$

$$= 0.008 \times 10^{-5} \tag{23}$$

$$\text{Similarly, } \sigma(\text{slope}_{3M + \text{Water}}) = 4\mu_0\rho g(0.174 \times 10^{-4}) \tag{24}$$

$$= 0.036 \times 10^{-5} \tag{25}$$

## 4.6 PROCEDURE

This has been heavily influenced by the Physics Lab Manual provided to us at IISER M, for the year 2013.

1. Calibrated the magnetic field produced by the electromagnet for various values of current in the Hall probe sensor. Fit the field vs. current data into a straight line. The probe was placed steady on a stand for all measurements.

   *This calibration may be unnecessary if one uses only the hall sensor reading for measuring the magnetic field*

2. The u-tube was cleaned with distilled water. Dried with compressed air and wiped clean from the outside as well.

3. Two solutions of different concentrations of Manganese sulphate were prepared and one of Ferric Chloride.

4. Placed one arm of the u-tube between the pole pieces so that the meniscus of the liquid is in the centre.

5. Noted the initial reading of the meniscus with a travelling microscope.

6. Measured the displacement $2h$ of the column of the liquid as a function of the applied field $B$.

7. Measured the field near the surface of the liquid in both arms.

8. Calculated the susceptibility using Equation 18 and plotted a graph to test the linear relation between the difference of square of magnetic fields with $h$.

## 4.7 RESULT

The susceptibility of $Mn^{2+}$ was found to be
$\chi_{2M} = (1.54 \pm 0.08) \times 10^{-6}$ and $\chi_{3M} = (11.1 \pm 0.036) \times 10^{-5}$

# 5 PLANCK'S CONSTANT FROM AN LED

April 9, 2013

## 5.1 AIM

To determine Planck's constant using a light emitting diode (LED).

## 5.2 APPARATUS

An LED connected to a voltmeter and ammeter with voltage control, a suitable oven with temperature readout

## 5.3 THEORY

### 5.3.1 *Motivation*

Planck's derivation of the energy for spectral energy density of black-body radiation was a landmark achievement which required the bold assumption that all resonators in the cavity, have discrete energy bundles, given by

$$\epsilon_n = nh\mu, \quad n = 0, 1, 2.. \tag{26}$$

### 5.3.2 *An Experimental Determination of 'h'*

There are various methods of determining the value of 'h'. Here we use an LED for this purpose. We use the fact that energy of a photon, $E = h\nu$ equals the energy gap $E_g = eV_0$ where $e$ is the electron charge and $V_0$ is the potential barrier from the n-doped to the p-doped side of the diode junction, without an external voltage. Since $\nu$ can be readily measure, and my thus be assumed to be known, we simply need to indirectly measure $V_o$ to determine $h$.

### 5.3.3 *Minimal Theory: LEDs*

We use take for granted, the current voltage characteristic equation for a diode as is given

$$I = Ae^{-\frac{V_0}{V_1}} e^{\frac{V}{V_1} - 1} \tag{27}$$

where $A$ is a proportionality constant, $V_0$ is the potential barrier described earlier (what we wish to determine), $V_1 = \eta kT/e$, wehre $k$

is the Boltzmann constant, $T$ is the absolute temperature, and $e$ is the electron charge and $V = V_m - RI$, which for our case can be approximated to $V = V_m$, where $V_m$ is the voltage across the external diode.

So we simply take natural log to obtain

$$\begin{aligned}
\ln I = \ln A - \frac{V_0}{V_1} + (\frac{V_m}{V_1} - 1) && (28)\\
= \frac{V_m - V_0}{V_1} + C && (29)\\
= \frac{(V_m - V_0)e}{\eta KT} + C && (30)\\
&& (31)
\end{aligned}$$

Now if we take $T$ to be constant and vary $I$ (or $V_m$), the slope may expressed as

$$\begin{aligned}
\frac{\Delta \ln I}{\Delta V_m} = 1/V_1 = \frac{e}{\eta kT} && (32)\\
\Rightarrow \eta = \frac{e\Delta V_m}{kT\Delta \ln I} && (33)
\end{aligned}$$

Now if we fix $T$ to approx. 1.8V and vary $I$ (with $T$) and plot $\ln I$ vs. $1/T$, the slope may be given by

$$\frac{\Delta \ln I}{\Delta(1/T)} = \frac{(V_m - V_0)e}{\eta k} \quad (34)$$

So using both of these, $V_0$ can be determined and as described earlier, $h$ can be calculated as

$$h = \frac{eV_0}{\nu} \quad (35)$$

And that's about it.

## 5.4 OBSERVATIONS AND CALCULATIONS

Observations have been appended at the end of this experiment.

Slope of the $V$ vs $\ln I$ was found to be $M_1 = 0.032$ with $R^2 = 0.999$. Slope of the $1/T$ vs. $\ln I$ graph was found to be $M_2 = -3.29 \times 10^3$ with $R^2 = 0.998$. Using these, we have

$h = (6.99 \pm 0.00645) \times 10^{-34}$

## 5.5 ERROR ANALYSIS

$$\begin{aligned}
\sigma(M_1) &= 3 \times 10^{-5} \\
\text{Where } M_1 \text{ is the slope from the first graph} \\
\text{Thus, the error in } \eta \text{ is given by} \\
\frac{e}{kT}\sigma(M_1) &= 0.0014 \\
\text{Similarly we have} \\
\sigma(M_2) &= 6.58 \\
\text{Error in } M_2 k\eta/e &= \text{\% error in } M_2 \text{ + \% error in } \eta \\
&= (0.02 + 0.053)\% \\
&= 0.55\% \\
\text{Error in } V_0 \text{ will then be} &= \text{absolute error in } M_2 k\eta/e \\
&= 0.00189V \\
\Rightarrow \text{Error in h} &= e\lambda(0.00189)/c \\
&= 0.00645 \times 10^{-34}
\end{aligned}$$

## 5.6 PROCEDURE

This has been heavily influenced by the Physics Lab Manual provided to us at IISER M, for the year 2013.

The apparatus in the lab has a two-way switch, that can be set to VI mode or to TI mode. The current is displayed in $\mu A$ when in the VI mode and in $mA$ when in the TI mode.

1. To draw V-I characteristics of LED
   a) Voltage Source
      i. Range: 0 - 1.95 V
      ii. Resolution: 1 mV
      iii. Accuracy=0.2 %
   b) Ammeter
      i. Range: 0 - 2000 μA
      ii. Resolution: 1 μA
      iii. Accuracy=0.2 %
   a) Connected the LED in the socket and switched on the power
   b) Switch the two way switch VI position. In this position, the first display would read voltage across the LED and the second display would read current.
   c) Increased the voltage gradually and tabulated the VI readings. There will not be any current till aprox. 1.5 V. Plotted ln I vs V and determined $\eta$.

2. Dependence of current on temperature at constant voltage
   a) Ammeter
      i. Range: 0 - 1.95 V
      ii. Resolution: 10 μA
   b) Temperature Readout for the Oven
      i. Range: Ambient to 65°C
      ii. Resolution: 0.1 °C

   a) Kept the mode switch to VI and adjusted the voltage slightly below the band gap voltage of the LED (1.8 V for Yellow/Red and 1.95V for Green)
   b) Switched the 'mode' switch to TI
   c) Inserted the LED into the oven and connected the oven to the socket. Before powering it, it was made sure the oven's set off and the temperature knob is set to the minimum. At this point the display would read the ambient temperature. Varied the temperature and read the current.
   d) Plotted $\ln I$ vs $\frac{1}{T}$

## 5.7 RESULT

The value of 'h' was found to be $h = (6.99 \pm 0.00645) \times 10^{-34}$

## COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede, for LaTeX.
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The latest version of this document is available online at:

https://github.com/toAtulArora/IISER_repo