

# 1<sup>st</sup> Science Physics Laboratory Manual

PHYC 10130  
Physics II Medical Science  
2017/18



Name.....

Partner's Name .....

Demonstrator .....

Group .....

Laboratory Time .....



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# Introduction

Physics is an experimental science. The theory that is presented in lectures has its origins in, and is validated by, experiment.

Laboratories are staged through the semester in parallel to the lectures. They serve a number of purposes:

- ***an opportunity, as a scientist, to test theories by conducting meaningful scientific experiments;***
- ***a means to enrich and deepen understanding of physical concepts presented in lectures;***
- ***an opportunity to develop experimental techniques, in particular skills of data analysis, the understanding of experimental uncertainty, and the development of graphical visualisation of data.***

Based on these skills, you are expected to present experimental results in a logical fashion (graphically and in calculations), to use units correctly and consistently, and to plot graphs with appropriate axis labels and scales. You will have to draw clear conclusions (as briefly as possible) from the experimental investigations, on what are the major findings of each experiment and whether or not they are consistent with your predictions. You should also demonstrate an appreciation of the concept of experimental uncertainty and estimate its impact on the final result.

Some of the experiments in the manual may appear similar to those at school, but the emphasis and expectations are likely to be different. Do not treat this manual as a 'cooking recipe' where you follow a prescription. Instead, understand what it is you are doing, why you are asked to plot certain quantities, and how experimental uncertainties affect your results. It is more important ***to understand and show your understanding*** in the write-ups than it is to rush through each experiment ticking the boxes.

This manual includes blanks for entering most of your observations. Additional space is included at the end of each experiment for other relevant information. All data, observations and conclusions should be entered in this manual. Graphs may be produced by hand or electronically (details of a simple computer package are provided) and should be secured to this manual.

There will be six 2-hour practical laboratories in this module evaluated by continual assessment. Note that each laboratory is worth 5% so each laboratory session makes a significant contribution to your final mark for the module. Consequently, attendance and application during the laboratories are of the utmost importance. At the end of each laboratory session, your demonstrator will collect your work and mark it.

## Laboratory Schedule:

Depending on your timetable, you will attend on either Tuesday or Thursday from 11 to 1pm.

Please consult the notice boards, Blackboard, or contact the lab manager, Thomas O'Reilly (Room Science East 1.41) to see which of the experiments you will be performing each week. This information is also summarized below.

Timetable:    Tuesday 11-1: Groups 1,3 and 6  
                   Thursday 11-1: Groups 2,4 and 7

UCD week	Semester 2 Week	Room		
		Science East 143	Science East 144	Science East 145
21	2	Beta-Ray: 1,7		Planck 3,4
22	3	Beta-Ray: 2,6		
24	5	Beta-Ray: 3,4		Planck 1,7
26	7	Half-Life: 1,7	Hydrogen Spect. 3,4	Planck 2,6
29	8	Half-Life: 2,6		
31	10	Half-Life: 3,4	Hydrogen Spect. 1,7	
32	11		Hydrogen Spect. 2,6	

## Grading Process

Grading is an important feedback for students and as such this is staged through the semester in close synchronisation with the labs. Students benefit from this feedback for continuous improvement through the semester. This is the grading process:

1. A lab script is graded and returned to the student in the subsequent scheduled lab slot.
2. Students resolve concerns regarding their grade with the demonstrator either during or immediately after this lab slot.
3. Grades are preliminary but can be expected to count towards a module grade once visible online. A grade is visible online within two weeks of the graded script being returned.

If the above doesn't happen, it is the student responsibility to resolve this with the demonstrator as early as possible.

## Lab Rules

1. No eating or drinking
2. Bags and belongings should be placed on the shelves provided in the labs
3. The school of physics lab manual for your module is available in print from the school of physics admin office and is also available online from the school of physics pages. Students are only permitted to start a lab where they have this school of physics manual in print.
4. It is the student's responsibility to attend an originally assigned lab slot. Zero grade is assigned by default for no attendance at this lab.

In the case of unavoidable absence, it is the student's responsibility to complete the lab in an alternative slot as soon as possible. The student is graded if doing so, however such a slot can't be guaranteed as lab numbers are strictly limited. The lab manager, Thomas O'Reilly (Room Science East 1.41), may be of help in discussing potential alternative lab times. Where best efforts have been made to attend an alternative but this still hasn't been possible, students should then discuss with their module coordinator.

5. Students work in pairs in the lab, however students are reminded that reports should be prepared individually and should comply with UCD plagiarism policy (see next page).

## UCD Plagiarism Statement

(taken from [http://www.ucd.ie/registry/academicsecretariat/docs/plagiarism\\_po.pdf](http://www.ucd.ie/registry/academicsecretariat/docs/plagiarism_po.pdf))

The creation of knowledge and wider understanding in all academic disciplines depends on building from existing sources of knowledge. The University upholds the principle of academic integrity, whereby appropriate acknowledgement is given to the contributions of others in any work, through appropriate internal citations and references. Students should be aware that good referencing is integral to the study of any subject and part of good academic practice.

***The University understands plagiarism to be the inclusion of another person's writings or ideas or works, in any formally presented work (including essays, theses, projects, laboratory reports, examinations, oral, poster or slide presentations) which form part of the assessment requirements for a module or programme of study, without due acknowledgement either wholly or in part of the original source of the material through appropriate citation.*** Plagiarism is a form of academic dishonesty, where ideas are presented falsely, either implicitly or explicitly, as being the original thought of the author's. The presentation of work, which contains the ideas, or work of others without appropriate attribution and citation, (other than information that can be generally accepted to be common knowledge which is generally known and does not require to be formally cited in a written piece of work) is an act of plagiarism. It can include the following:

1. Presenting work authored by a third party, including other students, friends, family, or work purchased through internet services;
2. Presenting work copied extensively with only minor textual changes from the internet, books, journals or any other source;
3. Improper paraphrasing, where a passage or idea is summarised without due acknowledgement of the original source;
4. Failing to include citation of all original sources;
5. Representing collaborative work as one's own;

Plagiarism is a serious academic offence. While plagiarism may be easy to commit unintentionally, it is defined by the act not the intention. All students are responsible for being familiar with the University's policy statement on plagiarism and are encouraged, if in doubt, to seek guidance from an academic member of staff. The University advocates a developmental approach to plagiarism and encourages students to adopt good academic practice by maintaining academic integrity in the presentation of all academic work.



Name: \_\_\_\_\_

Student No: \_\_\_\_\_

Date: \_\_\_\_\_ Partner: \_\_\_\_\_ Demonstrator: \_\_\_\_\_

## Electrons in Atoms: The Spectrum of atomic Hydrogen

### Introduction

The aim of this experiment is to observe the spectrum of hydrogen, to explain the spectrum in terms of the motion of electrons between discrete energy levels in the hydrogen atom and to evaluate a constant that is fundamental to calculating the wavelengths of the lines in the spectrum of hydrogen. The spectral emission lines that are seen in the visible region of the spectrum (red through violet) belong to the *Balmer* series and the positions of these lines may be determined using a spectrometer. From the observed wavelengths, the Rydberg formula may be applied and the Rydberg constant obtained.

### Background theory and historical perspective

At the turn of the last century measurement of the wavelengths of spectral lines in the light given off by low pressure hydrogen gas in an electrical discharge gave very consistent, highly repeatable results. The emission of light came to be understood in terms of electrons moving between discrete energy levels. The wavelengths of the lines fitted a very regular pattern. It was found that all of the wavelengths,  $\lambda_i$ , could be

calculated by using the Rydberg formula: 
$$\frac{1}{\lambda_{f,i}} = R \left[ \left( \frac{1}{n_f} \right)^2 - \left( \frac{1}{n_i} \right)^2 \right] \quad (\text{Eq. 1})$$

Here,  $n_f$  and  $n_i$  are both integers (called the principal quantum numbers) with  $n_i > n_f$ .  $R$  is a constant known as the Rydberg constant. These numbers were originally fitted to the series without any understanding of their physical meaning. However, most physicists felt that something basic must be inherent in such a simple equation. **Niels Bohr** was one of them. Having worked with Rutherford, he was aware of the nuclear model of the atom. In 1913 he postulated:

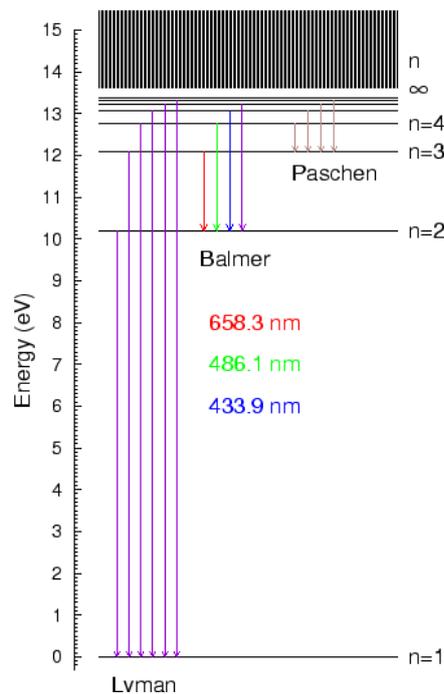
- that the electron in the hydrogen atom is in circular motion (in orbit) about the nucleus (which he assumed to be stationary),
- that it can only exist without radiating electromagnetic energy in certain "allowed" states of definite energy,
- that these were specified by quantised values  $nh/2\pi$  where  $h$  is Planck's constant and  $n$  is an integer,

- that transitions between these "allowed" states can occur only if photon emission or absorption occurs and the photon energy must be equal to the energy difference between the initial and final states. The photon energy ( $E$ ) is

given by:

$$E_i - E_f = hf \quad (\text{Eq. 2})$$

Based on this model, we can state that the number  $n_i$  refers to the initial (or upper) level. The values for  $n_f$  are lower than those of  $n_i$ , as they refer to the lower (or final) level involved in the electronic transition which results in the emission of light. The value of  $n_f$  is 2 for the Balmer series, as all of the electronic transitions terminate with the electron in the  $n = 2$  level. The first three of these series (electrons "falling" to  $n = 1$ ,  $n = 2$  and  $n = 3$ ) are illustrated in Fig.2 below. The Balmer series involves electrons moving between  $n_i = 3, 4, 5, 6, 7, \dots$  to  $n_f = 2$ . Three transitions in this series are shown below.



Identify the series of transitions (Lyman, Balmer or Paschen) that occur at the longest wavelength. Explain your reasoning.

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Calculate the energy of a photon in the red region of the spectrum ( $\lambda = 658 \text{ nm}$ ), using equation 2 above and the fact that the the speed of light ( $3 \times 10^8 \text{ ms}^{-1}$ ) is related to the wavelength ( $\lambda$ ) and frequency ( $f$ ) by the equation  $c = \lambda f$ .

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Using these postulates, Coulomb's law, and Newtonian mechanics, Bohr was able to derive the above equation from first principles and express the Rydberg constant in the form:

$$R = \frac{me^4}{8c\epsilon_0^2h^3} \quad (\text{Eq. 3})$$

Calculate the value of R, given the following values:

m, the mass of the electron =  $9.11 \times 10^{-31} \text{ kg}$ .

e, the charge on the electron =  $1.60 \times 10^{-19} \text{ C}$ .

$\epsilon_0$ , the permittivity of a vacuum =  $8.85 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2}$

h, Planck's constant =  $6.63 \times 10^{-34} \text{ Js}$ .

c, speed of light =  $3.00 \times 10^8 \text{ ms}^{-1}$

Fill in the table below using equation 1, and the value for R above to calculate  $\lambda$  for the numbers  $n_i = 3, 4, 5$  and  $n_f = 2$ .

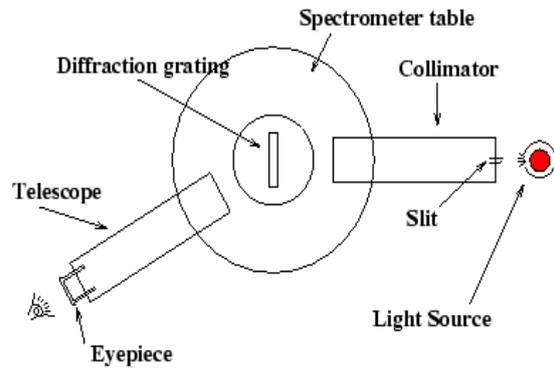
	$n_i = 3$	$n_i = 4$	$n_i = 5$
$(1/n_f)^2 - (1/n_i)^2$			
$\lambda_i$			

The results of the Bohr Theory were not perfect, but they were close enough to point the physics community in the proper direction to more fully develop the new quantum physics.

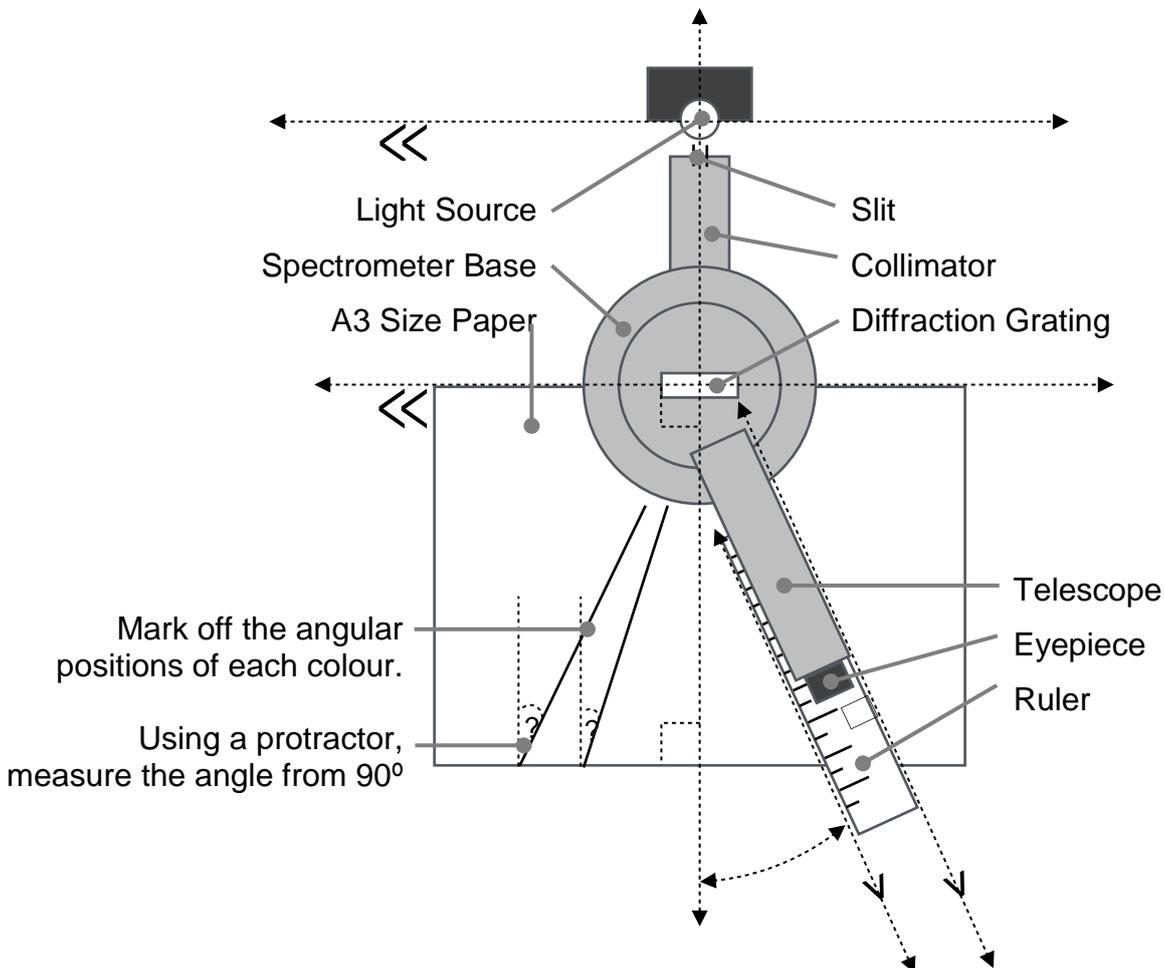
The purpose of this experiment is to use the spectrometer to observe that angles at which different wavelengths (colours) of light are diffracted and to calculate those wavelengths. This will allow you to verify the value of the Rydberg constant.

Procedure:

The experimental arrangement and a schematic of the spectrometer are shown below. The hydrogen discharge tube (light source) is positioned in front of the entrance slit of the spectrometer.



Setup the apparatus as shown in the diagram below, making sure to position the slits of the collimator directly in front of the light source. Align the diffraction grating and long edge of the sheet of A3 paper so that they are parallel with each other and perpendicular to the collimator and light source.



The spectrometer is adjusted as follows: **(1)** Set the entrance slit vertically. **(2)** Adjust the length of the collimator until the mark on the inner barrel is just visible. At this setting the light emerging will be collimated. **(3)** Set the grating perpendicular to the collimator and with the grooves vertical. **(4)** Align the telescope with the collimator when an image of the entrance slit will be seen. **(5)** Adjust the eyepiece until the crosswire is in sharp focus. **(6)** Adjust the length of the telescope until the image of the slit is in sharp focus. **(7)** Point the spectrometer directly at the discharge tube so that the light through the entrance slit is as bright as possible.

With the collimator and telescope in a straight line, the light viewed is the zero order line ( $m=0$ ) from the diffraction grating. All of the colours from the lamp are viewed simultaneously at the zero order. The telescope arm is rotated to the left whilst looking through the eyepiece until a coloured spectral line appears centered in the crosshairs of the telescope. Use a ruler aligned to the telescope to mark the line on the A3 sheet of paper. Using a protractor measure the angle this line creates from perpendicular and label it  $\theta_L$ . Continue rotating the telescope to the left and repeat the process until no more spectral lines are found. Return the telescope back through the centre line and repeat the procedure this time rotating to the right and labeling the angles  $\theta_R$ .

Record the data in the table below. By taking the average reading between  $\theta_L$  and  $\theta_R$ , correction is made for any slight deviation from the perpendicular of the diffraction grating to the optic axis of the spectrometer.

Colour	$n_i$	$1/n_i^2$	$m$	$\theta_L$	$\theta_R$	$\theta_m = (\theta_L - \theta_R) / 2$	$\lambda_i$	Mean $\lambda_i$	$1/\lambda_i$
Purple	5		1						
			2						
Blue-Green	4		1						
			2						
Red	3		1						
			2						







Name: \_\_\_\_\_

Student No: \_\_\_\_\_

Date: \_\_\_\_\_ Partner: \_\_\_\_\_ Demonstrator: \_\_\_\_\_

## The Absorption of $\beta$ -rays by Materials

Nuclear Emissions historically have been classified as  $\alpha$ -rays,  $\beta$ -rays or  $\gamma$ -rays. Each is due to a very different process.  $\alpha$ -rays consist of two protons and two neutrons and are caused by the strong force.  $\beta$ -rays are energetic electrons liberated through the weak force.  $\gamma$ -rays are due to electromagnetic interactions of the nucleus.

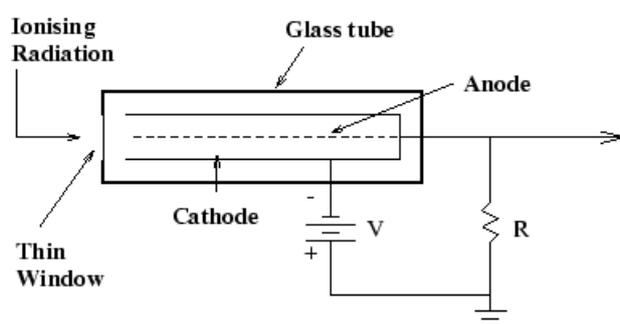
This experiment investigates how materials absorb  $\beta$ -rays, which is important in estimating the effects of radioactivity and in creating effective shielding.

### Apparatus

$\beta$ -rays are detected using a Geiger counter which consists of a Geiger-Muller tube and associated electronics. Each charged particle entering the tube is detected and the total number of counts displayed.

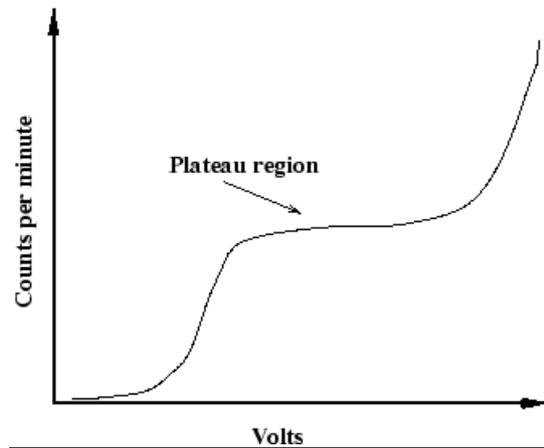
At the heart of the Geiger counter is a Geiger-Muller tube that consists of a sealed cavity that contains a thin-walled metallic cylinder with a wire positioned along the axis of the cylinder. The cavity contains a mixture of gases at very low pressure. Under normal operation, the cylinder is connected to the negative side of a high power voltage supply.

A charged particle passing through the gas ionises a gas molecule, the resulting electron is attracted by the central wire and the positive ion is attracted towards the cylindrical electrode. There is a very high electric field close to the central wire and the approaching



electrons are accelerated and gain a lot of kinetic energy. These high energy electrons undergo collisions with the gas molecules causing more and more ionisations. The multiplication of ions by this process is known as an "avalanche" and continues until there is a complete electrical discharge along the entire length of the electrode. A sudden pulse of current appears in the external circuit and the potential difference created across the resistor, R, results in a signal which is passed to the counter/rate-meter.

At low voltages, the avalanche process is inhibited and very few counts will be measured, while at high voltages too many counts will be measured as the avalanche process continuously ionises the gas within the tube. The flat portion of the curve where the counting rate is nearly constant over a reasonable voltage range, is called the **Geiger plateau**. Once the plateau is determined for a given Geiger-Muller tube, one should operate the tube with a voltage close to the middle of the plateau.



### Procedure

Set the detector voltage to the mid-point of the plateau (if necessary determine the plateau position). With the radioactive source well away from the GM tube count the background radiation for 5 minutes and hence find the background count per minute.

Background Rate = $\pm$ counts/minute
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Your source of  $\beta$ -rays is Thallium204 which decays with a half-life of 3.78 years - thus the activity of the source will remain constant during the course of the experiment. Place the source directly below the entrance window of the Geiger-Muller tube and adjust the height until a count rate of approximately 3600 counts per minute (or as high as you can achieve) is recorded with no absorber in position. This is the optimum position of the detector with respect to the source and neither counter nor source should be moved for the remainder of the experiment. You will need to leave room to insert several mylar foils between the source and the detector.



From your graph, calculate the mass per unit area of absorber that would give rates of 1000 and 3000 counts per minute.

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Investigation 2: Find the absorption coefficient of mylar

The  $\beta$ -particles are absorbed exponentially according to the equation

$$N = N_0 \exp(-\lambda x) \quad (\text{Eq.1})$$

where  $N_0$  are the number present at  $x = 0$ ,  $N$  are the number still present after travelling a distance  $x$  in the material and  $\lambda$  is the absorption coefficient. Taking the natural log of Eq.1 gives

$$\ln N = \ln N_0 - \lambda x \quad (\text{Eq.2})$$

From the data you have already taken for mylar, make a plot of  $\ln N$  against  $x$ . (You will need to calculate  $x$  by finding the thickness of one foil using a micrometer screw and multiplying by the number of foils.)

Number of Absorbers	$x$ (m)	$N$ Background subtracted rate (counts/minute)	$\ln N$

Write down the slope and intercept of the graph.

Slope =

Intercept =







The radioactive Decay Law:

The decay reaction proceeds at a rate which depends only on the nature of  ${}_{49}\text{In}^{116}$  and the number of  ${}_{49}\text{In}^{116}$  atoms present at any time. Thus,

$$-\frac{dN}{dt} \propto N \quad (\text{Eq.1})$$

where  $dN/dt$ , the decay rate, is proportional to the number of atoms,  $N$ , present at time  $t$ . Rewriting with  $\lambda$  as a constant of proportionality we obtain

$$-\frac{dN}{dt} = \lambda N \quad (\text{Eq. 2})$$

$\lambda$  is known as the **decay constant or disintegration constant** of the radioactive material. Each different type of radioactive atom has a characteristic  $\lambda$ .

Eq. 2 can be solved by integrating to give

$$N = N_0 e^{-\lambda t} \quad (\text{Eq. 3})$$

where  $N_0$  is the number of nuclei present at  $t = 0$ .

A more intuitive number which characterises the decay is the **half life**: the time after which only half the original sample remains. With this definition and using Eq. 3,

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}} \quad (\text{Eq. 4})$$

showing the half-life is related to the decay constant by

$$T_{1/2} = \ln 2 / \lambda \quad (\text{Eq. 5})$$

In this experiment you will not measure the total number of atoms in the sample at a given time but will count an observed rate,  $R$ , which is proportional to the rate,  $dN/dt$ , at which atoms decay. Using Eq.2 and 3,

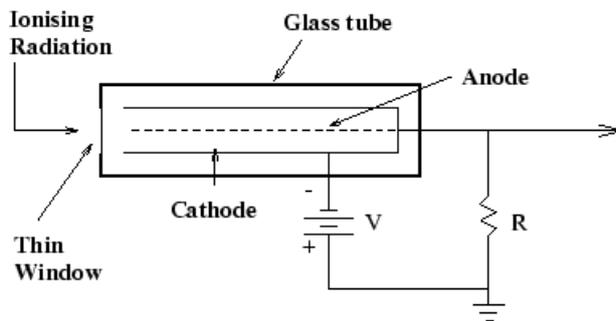
$$R = \frac{dN}{dt} = -\lambda N = -\lambda N_0 e^{-\lambda t} = \left( \frac{dN}{dt} \right)_0 e^{-\lambda t} = R_0 e^{-\lambda t} \quad (\text{Eq. 6})$$

and so

$$R = R_0 e^{-\lambda t} \quad (\text{Eq.7})$$

## Apparatus

The Geiger counter consists of a Geiger-Muller tube and associated electronics. Each charged particle (in this experiment it will be beta-rays) entering the tube is detected and the total number of counts displayed.

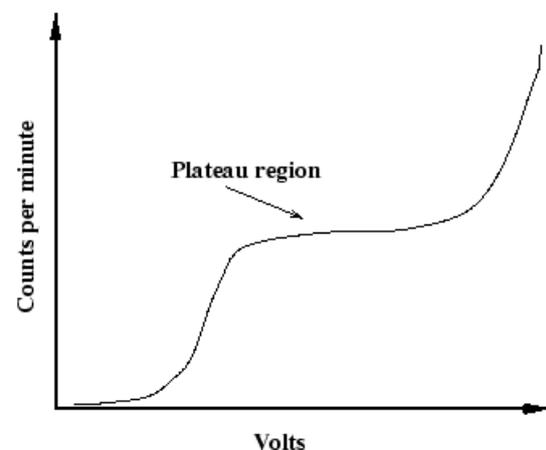


At the heart of the Geiger counter is a Geiger-Muller tube that consists of a sealed cavity that contains a thin-walled metallic cylinder with a wire positioned along the axis of the cylinder.

The cavity contains a mixture of gases at very low pressure. Under normal operation, the cylinder is connected to the negative side of a high power voltage supply.

A charged particle passing through the gas ionises a gas molecule, the resulting electron is attracted by the central wire and the positive ion is attracted towards the cylindrical electrode. There is a very high electric field close to the central wire and the approaching electrons are accelerated and gain a lot of kinetic energy. These high energy electrons undergo collisions with the gas molecules causing more and more ionisations. The multiplication of ions by this process is known as an "avalanche" and continues until there is a complete electrical discharge along the entire length of the electrode. A sudden pulse of current appears in the external circuit and the potential difference created across the resistor, R, results in a signal which is passed to the counter/rate-meter.

At low voltages, the avalanche process is inhibited and very few counts will be measured, while at high voltages too many counts will be measured as the avalanche process continuously ionises the gas within the tube. The flat portion of the curve where the counting rate is nearly constant over a reasonable voltage range, is called the **Geiger plateau**. Once the plateau is determined for a given Geiger-Muller tube, one should operate the tube with a voltage close to the middle of the plateau.



Since alpha and beta particles are charged they can be detected by the Geiger counter. Gamma rays will only be detected in the unlikely event that they interact with the gas molecules within the tube. To allow the  $\alpha$ - and  $\beta$ -particles to enter the tube, there is a

very thin delicate mica window at one end of the cylindrical cavity. ***This should not be touched as it is easily broken.***

Procedure:

Set the Geiger-Muller tube voltage to the value given for your particular apparatus (**380V**). This corresponds to the midpoint of the plateau region.

With the source well away from the Geiger-Muller determine the **background rate (counts / minute),  $R_b$** , by counting for 4 minutes.

The radioactive indium foil, housed within a protective covering, is placed on the bench and, to get the maximum count rate, the Geiger-Muller tube is lowered until it is as close as possible to the source.

You will need to measure the number of counts in a series of four-minute intervals. The stop-clock and counter/rate-meter should be reset and started simultaneously. To measure the counts in the first four-minute interval, the counter should be stopped after 4 minutes but the stop-clock should continue to run. The count rate,  $R$  (allowing for background), should be calculated. Reset the counter, but not the continuously running stop-clock. Measure the number of counts in the four-minute interval starting at time = 5 minutes and then repeat the measurement by counting for 4 minutes at strictly regular intervals of five minutes. Tabulate the results below.

Time (seconds)	# counts	# counts (background subtracted)	$\sqrt{\#}$ counts	Rate (counts/second)	Uncertainty in Rate (counts/sec)	ln (Rate)
0						

Time (seconds)	# counts	# counts (background subtracted)	$\sqrt{\#}$ counts	Rate (counts/second)	Uncertainty in Rate (counts/sec)	In (Rate)
0						

Measurements should continue until the count rate is approximately one quarter of the original count rate. Note that the statistical uncertainty on the number of counts is the square root of the number of counts.

Plot the rate,  $R$ , against time,  $t$ .

What do you observe?

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Take the natural logarithm of both sides of Eq.7.







Name: \_\_\_\_\_

Student No: \_\_\_\_\_

Date: \_\_\_\_\_ Partner: \_\_\_\_\_ Demonstrator: \_\_\_\_\_

## A Measurement of Planck's Constant.

### Introduction

This experiment measures the ratio of Planck's constant,  $h$ , to the charge on the electron,  $e$ . These are two of the fundamental constants of nature: electricity and magnetism are quantised in terms of integral numbers of  $e$ , while radiation is emitted or absorbed in discrete energy packets proportional to  $h$ . A more sophisticated interpretation of  $h$  is that it is the fundamental quantum of **action** (defined as energy multiplied by time) and thus defines the limit to which any experimental measurement can be made.

### Background theory and historical perspective

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws, but as scientists continued working, inconsistencies that could not be explained began to show up. In particular, classical physics could not explain the emission of radiation from an idealised hot object, a '**black body**' which completely absorbs all radiant energy falling upon it, reaches some equilibrium temperature, and then reemits that energy as quickly as it absorbs it.

In 1901 Planck published his law of radiation. In it he stated that the atoms in the black body behaved as oscillators and that any oscillator or indeed, any similar physical system has a **discrete** set of possible energy values or levels; energies between these values never occur. The emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, called a **photon**. The energy,  $E$ , of the photon is related to the frequency of radiation,  $f$ , by:

$$E=hf \quad (\text{Eq.1})$$

Planck's constant was found to have significance beyond relating the frequency of the radiation and the energy of the associated photon and became a cornerstone of the quantum mechanical view of the subatomic world. In 1918, Planck was awarded the Nobel prize for introducing the quantum theory of light.

The photoelectric effect

Light striking a material, causing electrons to be emitted immediately (the Photoelectric Effect). Classical theory could not explain two features of this phenomenon.

- Firstly, one might expect classically that increasing the amplitude of the incident light would increase the energy of the electrons emitted. However experimentally it was shown that increasing the amplitude of the incident light only increased the *number* of electrons emitted.
- Secondly, it was found experimentally that the kinetic energy of the electrons depended on the *frequency* (or colour) of the light and that below a certain frequency threshold *no electrons would be emitted*, even if the intensity of the incident light was extremely high.

Why, classically, would increasing the amplitude of the incident light increase the energy of the electrons emitted?

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Why, classically, should the kinetic energy of the electrons not depend on the *frequency* (or colour) of the light?

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Einstein explained the effect by applying Planck's theory. He said light was made up of discrete packets of energy called **photons** having an energy  $E=hf$ . The photon gives up all its energy to an electron which uses some of it to escape from the material with the rest appearing in the form of kinetic energy of the emitted electron. Applying conservation of energy to the most energetic electrons emitted gives

$$E = h \cdot f = KE_{max} + W_0 \quad (\text{Eq. 2})$$

Where  $E = hf$  is the photon energy.  $KE_{max}$  is the maximum kinetic energy of the emitted photoelectrons, and  $W_0$  is the minimum energy needed to remove them from the surface of the material (the work function). This interpretation explains why higher frequency light produces higher energy photoelectrons, independent of intensity, while increased intensity only increases the number of electrons emitted (or the photoelectron current). Einstein received the Nobel prize for this work (and not for relativity!) which is somewhat ironic given his later dislike of the quantum theory and his famous assertion that 'God doesn't play dice'.

Why, quantum mechanically does increasing the amplitude of the incident light not increase the energy of the electrons emitted?

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Why, quantum mechanically, does the kinetic energy of the electrons depend on the *frequency* (or colour) of the light?

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### The photoelectric effect in the laboratory

A photon is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum  $W_0$  of its energy to escape the cathode, leaving it with a maximum kinetic energy of  $KE_{max}$ . The emitted electrons reach the collector electrode of the tube when it is at a positive potential and can be measured as a photoelectric current. However, by applying a reverse potential  $V$  the photoelectric current can be stopped.  $KE_{max}$  can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero. Relating kinetic energy to stopping potential,  $V_s$ , gives the equation:

$$KE_{max} = V_s \cdot e \quad (\text{Eq.3})$$

Substituting into Eq. 2 gives

$$V_s = (h/e)f - (W_0/e) \quad (\text{Eq. 4})$$

where  $e$  and  $h$  are universal constants, and  $W_0$  is a constant for a particular cathode material.

#### Apparatus

The apparatus consists of a special cathode from which electrons can be emitted, a mercury vapour lamp to illuminate the cathode, and various filters to select particular wavelengths of light. A multimeter measures the stopping potential of the photoelectrons.

Monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function,  $W_0$ . Photoelectrons ejected from the cathode are collected by the anode.

The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilises. This final voltage between the anode and cathode is therefore the stopping potential of the photoelectrons. It can be measured directly using a digital voltmeter.







## Graphing

Many of the experiments in the 1st Year laboratory involve the plotting of a graph. Graphs are very important in Physics as they provide a simple display of the results obtained in an experiment and of the relationship between two variables. More accurate and reliable information can be obtained from a graph than from the analysis of any particular set of results.

### ***Plotting graphs by hand:***

- (1) *Scale:* It is important to choose the scales so as to make full use of the squared page. The scale divisions should be chosen for convenience; that is, one unit is either 1, 2 or 5 times a power of ten e.g. 0.5, 5, 100 etc., but never 3, 7, 9 etc.
- (2) *Marking the points:* Readings should be indicated on the graph by a ringed dot ⊗ and drawn with pencil, so that it is possible to erase and correct any unsatisfactory data.
- (3) *Joining the points:* In the case of a straight line which indicates a direct proportion between the variables, the ruler is positioned so that the line drawn will pass through as many points as possible. Those points which do not lie on the line should be equally distributed on both sides of the line. A point which lies away from this line can be regarded as 'doubtful' and a recheck made on the readings. In the case of a curve, the individual experimental points are not joined with straight lines but a smooth curve is drawn through them so that as many as possible lie on the curve.
- (4) *Units:* The graph is drawn on squared page. Each graph should carry **title** at the top e.g. Time squared vs. Length. The axes should be labelled with the name and units of the quantities involved.
- (5) In the case of a straight-line graph, the equation of the line representing the relationship between the quantities x and y may be expressed in the form

$$y = mx + c$$

where **m** is the slope of the line and **c** the intercept on the y-axis. The slope may be positive or negative. Many experiments require an accurate reading of the slope of a line.

## Using JagFit

In the examples above we have somewhat causally referred to the '**best fit**' through the data. What we mean by this, is *the theoretical curve which comes closest to the data points having due regard for the experimental uncertainties*.

This is more or less what you tried to do by eye, but how could you tell that you indeed did have the best fit and what method did you use to work out statistical uncertainties on the slope and intercept?

*The theoretical curve which comes closest to the data points having due regard for the experimental uncertainties* can be defined more rigorously<sup>1</sup> and the mathematical definition allows you to calculate explicitly what the best fit would be for a given data set and theoretical model. However, the mathematics is tricky and tedious, as is drawing plots by hand and for that reason....

We can use a computer to speed up the plotting of experimental data and to improve the precision of parameter estimation.

In the laboratories a plotting programme called Jagfit is installed on the computers. Jagfit is freely available for download from this address:

<http://www.southalabama.edu/physics/software/software.htm>



Double-click on the JagFit icon to start the program. The working of JagFit is fairly intuitive. Enter your data in the columns on the left.

- Under **Graph**, select the columns to graph, and the name for the axes.
- Under **Error Method**, you can include uncertainties on the points.
- Under **Tools**, you can fit the data using a function as defined under **Fitting Function**. Normally you will just perform a linear fit.

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<sup>1</sup> If you want to know more about this equation, why it works, or how to solve it, ask your demonstrator or read about 'least square fitting' in a text book on data analysis or statistics.

# Experimental Uncertainties

## Experimental Uncertainties

When you make a scientific measurement there is some 'true' value that you are trying to estimate and your equipment has some intrinsic **uncertainty**. Thus you can only estimate the 'true' value up to the uncertainty inherent within your method or your equipment. Conventionally you write down your measurement followed by the symbol  $\pm$ , followed by the uncertainty. A surveying company might report their results as  $245 \pm 5$  km,  $253 \pm 1$  km,  $254.2 \pm 0.1$  km. You can interpret the second number as the 'margin of error' or the **uncertainty** on the measurement. If your uncertainties can be described using a Gaussian distribution, (which is true most of the time), then the true value lies within one or two units of uncertainty from the measured value. There is only a 5% chance that the true value is greater than two units of uncertainty away, and a 1% chance that it is greater than three units.

Errors may be divided into two classes, systematic and random. A **systematic error** is one which is constant throughout a set of readings. A **random error** is one which varies and which is equally likely to be positive or negative. Random errors are always present in an experiment and in the absence of systematic errors cause successive readings to spread about the true value of the quantity. If in addition a systematic error is present, the spread is not about the true value but about some displaced value.

Estimating the experimental uncertainty is at least as important as getting the central value, since it determines the range in which the truth lies. Frequently scientists will spend much more time estimating the experimental uncertainty than finding the central value.

For most of the experiments you will do in first year it is sufficient to:

1. Consider the various uncertainties that could have affected your result;
2. Roughly estimate the size of each;
3. Find the source with the largest relative uncertainty;
4. Find the effect of that source on your result.

### 1. How do you find the sources of uncertainty?

In all the experiments you will have made a number of measurements that are combined together to produce a final result for some physical quantity. Think about the uncertainties that could enter each measurement, due to both the intrinsic precision of your tools and changeability of the environment.

### 2. How do you find the **size** of each source of uncertainty?

Use common sense!

If you are reading a scale, how precisely can you read off the gradations?

If a display or instrument is unstable or moves, over what range does it change?

If you are timing something, what are your reaction speeds?

If you are viewing something by eye, with what precision can you line it up?

If you are counting something, the uncertainty in the number of counts is generally the square root of the number of counts.

Sometimes, a good way to estimate the size of a source of uncertainty is to repeat the measurement a few times and see by how much your reading varies on average.

### 3. Find the source with the largest relative uncertainty

#### 4. Find the effect of that source on your result

Once you have identified the largest source of uncertainty, you must figure out how that affects your final result. There are two ways to do this: (i) calculate the uncertainty on your final result by changing the source value by its uncertainty; (ii) plug your numbers into a formula (but you have to know which formula to use!)

##### 4.1 Method 1: Recalculating your result by changing the source values.

- From your measurements, calculate the final result. Call this  $f$ , your answer.
- Now move the value of the source up by its uncertainty. Recalculate the final result. Call this  $f^+$ .
- The uncertainty on the final result is the difference in these values: i.e.  $|f - f^+|$

You could also have moved the value of the source down by its uncertainty and recalculated the final result. You should get the same answer (in most situations).

If you like to express this in mathematics, let  $x \pm \delta_x$  be the measurement and  $f(x)$  the result you want to calculate, then  $\delta_f = |f(x + \delta_x) - f(x)|$  and your final answer is  $f \pm \delta_f$ .

##### 4.2 Method 2: Using a formula.

**Suppose you calculate  $f$  which is some function of variable  $x$  with an associated uncertainty  $\Delta x$ . What is the uncertainty  $\Delta f$  on  $f$  ?**

For errors with a Gaussian distribution, the uncertainty on  $f$ ,  $\Delta f$ , is given by

$$\Delta f = \frac{\partial f}{\partial x} \Delta x.$$

Example 1:  $f = Ax$

You just multiply  $x$  by a constant  $A$ ; then  $\Delta f = A \Delta x$ .

**Suppose you calculate  $f$  which is some function of variables  $x$  and  $y$ , with associated uncertainties  $\Delta x$  and  $\Delta y$ . What is the uncertainty  $\Delta f$  on  $f$  ?**

For errors with Gaussian distributions, the uncertainty on  $f$ ,  $\Delta f$ , is given by

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x} \Delta x\right)^2 + \left(\frac{\partial f}{\partial y} \Delta y\right)^2}$$

Example 2:  $f = x - y$

You add or subtract two independent measurements; then  $\Delta f = \sqrt{\Delta x^2 + \Delta y^2}$ .

(Short cut: If one error is at least twice as big as the other, you can ignore the smaller error. So in this case if  $\Delta x > 2\Delta y$  then  $\Delta f \approx \Delta x$ .)