The Hashemite University

Department of Physics

Computer-based Physics Experiments

Laboratory Manual for Physics 2102283

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Preface

Physics is the science that seeks to explain how our universe, and everything in it, works. Experimentation involves observing how things work under certain conditions and theory seeks to understand the observations already made and make predictions for new experiments to be carried out.

This course, certains a set of virtual laboratory experiments, software that emulates a real physics lab. So you will be doing simulated physics experiments, that are taken from commercial companies, mainly Physics Academy Software.

In the virtual laboratory, you can do many of the things you do in a real lab: set up experiments, predict outcomes, make measurements and perform observations. But you can also do things that can not be done in a real lab. The course is designed to target mainly second year physics students at the Hashemite University. As a prerequisit for this course, students must pass the required three courses in general physics offered at the Hashemite University.

A final word that the author would like to say is a warning for both instructors and students not to think of the virtual laboratory as a substitute for real laboratory experience. On the contrary, think of it as preparation for a real lab. Many of the experiments that you will do in software can be done easily with hardware.

Contents

1   Origin, the graphical software

Origin is a friendly graphical software. It provides power and speed for technical graphics and data analysis under windows. It is one of the friendlist and easy to use graphical softwares. You can easily import data or open excel worksheets directly. Two and three dimensional graphs are created quickly and effortlessly with just a single click. Graph elements can be modified by double clicking to get a specialized dialog box.

When you start origin, it opens a new project displaying a worksheet window. You can insert data in one of two ways;

1. Direct inserting data in the x and y columns.

2. Import data by choosing from the main menue $file/Import/single$ $ASCII/$ (for importing one data file) and $Multiple$ $ASCII$ (for importing more than one data file).

Example:-
Plot a graph between x-axis and y-axis for the following points;
(x, y)=(1, 1), (2, 4), (3, 9), (4, 16)

1. Choose the style $line + symbol$ from the $plot$ icon in the main bar.

2. Adjust the x and y ranges to $x\ \epsilon(0, 5)$ and $y\ \epsilon(0, 20)$, respectively, with a suitable $increment$.

3. Let the x-axis represent displacement measured in meters (m) and the y-axis represent time measured in seconds (s), by changing the axis.

4. Inseret a title.

5. Find the equation of this linear relation.
   Note: Go to $analysis$ in the toolbar and choose $fit\ linear$. This implies that the program will give you the fitting equation with the slope and y-intercept in a small window.

Exercise:-
Inseret the following data in a notpad file, then import them in origin and repeat the steps in the above example.
(x, y)= (-5, -125), (-3, -27), (-1, -1), (0, 0), (1, 1), (3, 9), (5, 125).

2 Coordinate Systems

2.1 Coordinate Systems

Theory

The space we live in is three-dimensional. This means that three numbers are required to specify the location of a point in space without ambiguity [Recall what you have learned in Mathematical Physics I]. These three numbers may be replaced by three independent variables. A point in space is an interception of three orthogonal surfaces. We use the cartezian coordinate system (x, y, z) to describe the position of an object. The three surfaces for the cartezian coordinate system are plane surfaces. Sometimes it is convenient to represent a point in its spherical or cylindrical coordinates. In this case the type intercepting surfaces in a point are not all plane surfaces.

The spherical coordinates of a point are (r, ϕ, θ). Two surfaces for the spherical coordinate system are curved and one is a plane surface. Specify them. Here, r is the distance from the origin, θ is the polar angle, and ϕ is the azimuthal angle. Their relation to cartezian coordinates (x, y, z) can be

$$x = r \, \sin \phi \, \cos \theta \tag{1}$$
$$y = r \, \sin \phi \, \sin \theta \tag{2}$$
$$z = r \, \cos \phi \tag{3}$$

The cylindrical coordinates of a point are (r, θ, z). Two surfaces for cylindrical coordinate system are plane surfaces and one is a curved surface. Specify them. Note that r is the distance to the point from the z-axis, θ has the same meaning as in spherical coordinates, and z is the same as the cartezian. The relationship with cartezian coordinates is

$$x = r \, \cos \theta \tag{4}$$
$$y = r \, \sin \theta \tag{5}$$
$$z = z \tag{6}$$

Experiment

In the demostration on your computer screen, you will see a window with two main menues; in the left menu you have the title *"Coordinate Systems"*. In the right menu you find three options to go to representing

cartezian, cylindrical and spherical coordinate systems.

Choose one coordinate system on the right menu and try to demostrate what the instructor has explained. You can play with the components on the left "*control window*". By the end of each demostration you should be able to recognise the three independent variables for each coordinate system, a randomly chosen point in space (seen as a black sphere in the lab.) and the position vector of this point. You can switch any of these elements on and off clicking on "*Display*" in the main menu and then switching elements *on* and *off*. Also, you can choose "*Experiment*" from the main menu and see what the choice "*Defaults*" can do.

In the control window the default parameters, for cartezian coordinates, the x-component, y-component and z-component are $70m$, $110m$ and $100m$, respectively.
For cylindrical coordinates the default parameters for r, θ, z are $130m$, $57.5°$ and $100m$, respectively.
For spherical coordinates the default parameters for r, θ, ϕ are $164m$, $57.5°$, $52.5°$, respectively.

Procedure:

1. **Cartesian coordinate**

   (a) Display the position vector.
   (b) play with the x, y and z-components and observe the direction of the position vector.

2. **Cylindrical coordinate**
   Display the position vector and the three cartesian components on your screen.

   (a) i. Calculate the three cartesian components for the point $(80, 70, 110)$ presented in cylindrical coordinates.
       ii. Record the cartesian components for the point $(80, 70, 110)$ from the control window.
      iii. Do the corresponding results agree?
   (b) Repeat step (a) for point $(52, 33, 90)$.

3. **Spherical coordinate**
   Display the position vector and the three cartesian components on your screen.

(a)   i. Calculate the three cartesian components for the point $(120, 30, 40)$ presented in spherical coordinates.

     ii. Record the cartesian components for the point $(120, 30, 40)$ from the control window.

     iii. Do the corresponding results agree?

(b) Repeat step (a) for point $(70, 22, 77)$.

3 Mechanics

This chapter consists of six sets of experiments; block on an incline, circular motion, center of mass, collision, simple harmonic oscillator and stress-strain.

3.1 Block on an Incline

Theory

Newton's second law;
"The acceleration ($\vec{a}$) of an object is directly proportional to the net force ($\sum \vec{F}$) acting on it and inversely proportional to it's mass (m)".

Consider an object of mass (m) placed on an incline with an x-axis along the incline and a y-axis perpendicular to the incline.

Newton's second law yields

$$\sum F_x = mg\sin\theta - f_r = ma_x \tag{7}$$

$$\sum F_y = mg\cos\theta = 0, \tag{8}$$

where f_r is the frictional force.

Notes:

1. When the block is at rest, $a_x = 0$, $f_r = f_s$, the static frictional force.

2. When the block is about to move, $a_x = 0$, $f_r = f_{s(max.)} = \mu_s N = \mu_s mg\cos\theta$.

3. When the block slides along the incline, $f_r = f_k = \mu_k N = \mu_k mg\cos\theta$.

Experiment

The setup on your screen consists of a block situated on an incline. In the control window the default parameters the inclination angle, static friction coefficient, kinetic friction coefficient and the mass of the block are 35°, 0.5, 0.3 and $10kg$, respectively.

Procedure:

I. Using default parameters answer the following;

1. Does the block slide?
2. What makes the block slide?
3. Write down the default parameters.
4. Calculate the force acting on the block along the incline.
5. Calculate the acceleration.

II. Set the experiment to default parameters and continue.

1. Change the angle of inclination slowly utill you arrive at a situation where the block is about to slide.

2. Compare the coefficient of static friction with the tangent of the inclination angle.

3. For the same situation (block about to move), check if this angle depends on the mass of the block.

III. Reset the experiment to default parameters and continue.

1. From the "*Display*" button choose "*velocity*" and "*acceleration*" and notice the velocity and acceleration vectors appearing on the screen (**Note:** Magnitude of a vector is proportional to length of this vector). Run the experiment and watch the magnitude of velocity and acceleration as the block slides. What do you see?

2. Plot two graphs for the frictional force versus time and acceleration versus time.

3.2 Simple Harmonic Oscillator

Theory

Each day we encounter many kinds of oscillatory motions. Oscillatory motion occures when the force acting on an object is proportional to the displacement of the body from some equilibrium position. If this force is always directed toward the equilibrium position, repetitive back-and-forth motion occures about this position. In this subsection, two cases are discussed; the simple harmonic motion and the damped motion.

Simple Harmonic Motion (No Damping):

Consider a physical system of a spring that is fixed at one end and attached to a block of mass (m) at the other end, where the mass is free to move on a horizontal frictionless surface.

The spring exerts a force on the block that is proportional to the displacement. This force is given by Hook's law:

$$F = -kx, \tag{9}$$

where x is the displacement from the equilibrium position. This force is called the restoring force because it is always directed toward the equilibrium position and, therefore, opposite to the displacement. Using equation (9), Newton's second law of motion gives

$$F = ma$$

$$m \frac{d^2}{dt^2} x = -kx \qquad \text{or} \qquad \ddot{x} + \frac{k}{m} x = 0 \tag{10}$$

A solution for this equation is

$$x = A \, \cos(\omega t + \phi) \tag{11}$$

where A is the amplitude of oscillation, $\omega = \sqrt{\frac{k}{m}}$ is the angular frequency and ϕ is the phase constant. The period of oscillation $T = \frac{2\pi}{\omega}$ is the time needed for the particle to complete one full cycle. The inverse of the period is called the frequency ($\nu = \frac{1}{T} = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$).

We can obtain the linear velocity and acceleration of a particle undergoing simple harmonic motion as follows;

$$v = \dot{x} = -\omega \; A \; \sin(\omega t + \phi) \tag{12}$$

$$a = \ddot{x} = -\omega^2 A \; \cos(\omega t + \phi) \tag{13}$$

For simple harmonic motion, the total mechanical energy $(E = K + U)$ is conserved, where $K = \frac{1}{2} \; kx^2$, $U = \frac{1}{2} \; mv^2$. It is given by the following relationship;

$$E = \frac{1}{2} \; kx^2 + \frac{1}{2} \; mv^2 \tag{14}$$

Using equations (11) and (12), the total energy becomes

$$E = \frac{1}{2} kA^2 \tag{15}$$

Damped Harmonic Motion:

In equation (15), energy is proportional to the square of the amplitude of the wave. In damped oscillations, the amplitude of the oscillation gradually decreases to zero as a result of friction. The frictional force is proportional to the speed of the block, the equation of motion (equation (10) becomes

$$\ddot{x} + \frac{k}{m} \; x + \frac{b}{m} \dot{x} = 0 \tag{16}$$

where b is a positive constant measured in kg/s. A solution for equation (16) is

$$x = A \; e^{-\frac{bt}{2m}} \cos(\omega' t + \phi), \tag{17}$$

where

$$\omega' = \sqrt{\frac{k}{m} - (\frac{b}{2m})^2} \tag{18}$$

Equations (17) and (18) are valid only for $b \geq 2\sqrt{km}$. If b has its largest possible value ($b = 2\sqrt{km}$), then $\omega' = 0$ and the displacement approaches the equilibrium point after a perturbation with no oscillation. This condition, called *critical damping*, is often the goal of mechanical engineers in

designing a system in which oscillations are meant to disappear in the shortest possible time. It is very obvious from equation (17) that the amplitude $\left(Ae^{-bt/2m}\right)$ decays exponentialy with time.

In damped harmonic motion, the energy of the oscillator is gradually dissipated by friction and falls eventualy to zero. The energy is given by

$$E(t) = \frac{1}{2}k \, (A \, e^{-\frac{bt}{2m}})^2$$
$$E(t) = E_0 \, e^{-\frac{bt}{m}}, \tag{19}$$

where $E_0 = \frac{1}{2}kA^2$ is the energy at $t = 0$.

Two final notes are

1. K, U, x, v, $a \equiv$ constants if there is no damping.

2. $E = K + U$ is equal to a constant value for the nondamped motion, and of decreases with time for damped motion.

Experiment

The setup on your screen consists of a spring connected to a mass with a hydrolic system. In the control window the default parameters the mass, spring constant, damping factor, period, natural angular frequency, natural frequency, initial displacement and initial velocity are $1kg$, $15N/m$, $0.4N.s/m$, $1.62s$, $3.87rad/s$, $0.616Hz$, $0.05m$ and 0, respectively.

Procedure:

1. "*Run*" the experiment with the default nombers for $b = 0$, 0.1, $0.5 N.s/m$. How does the amplitude of oscillation change with time in each case?

2. **No damping**

   (a) **i.** Calculate the maximum amplitude of the displacement, velocity and acceleration for the default parameters.

   ii. Run the experiment with the default numbers. Plot the displacement, velocity and acceleration versus time. Do the calculated value agree with that in the graph?

   (b) On the graph produced in step (2.a.ii) repeate step (2.a) for $m = 2kg$. How does the period depend on the mass?

   (c) Calculate the restoring force (spring force) for the default parameters (let spring constant be k_1). Doubled the spring constant (k_2), then halve it (k_3). How does the restoring force depend on the spring constant?

   (d) **i.** Calculate the total energy for the default parameters.

   ii. Plot total energy versus time graph. Is the total energy changed when mass or spring constant is changed? Explain your answer.

3. **Damped motion**

   (I) For $b = 0.1 N.s/m$:

   (a) **i.** Calculate the maximum amplitude of the displacement, velocity and acceleration for the default parameters.

   ii. Run the experiment with the default numbers. Plot the displacement, velocity and acceleration versus time. Do the calculated value agree with that in the graph?

   (b) On the graph produced in step (3.I.a.ii) repeate the step (3.I.a) for m = $2kg$. How does the period depend on the mass?

   (c) Calculate the restoring force (spring force) for the default parameters (let spring constant be k_1). Doubled spring constant (k_2), then halve it (k_3). How does the restoring force depend on the spring constant?

   (d) **i.** Calculate the total energy for the default parameters.

ii. Plot total energy versus time graph. Is the total energy changed when mass or spring constant or damping factor is changed? Explain your answer.

3.3 Stress and Strain

Theory

Solids are composed of atoms that are not in rigid contact. Atoms do not have hard surfaces that can pack closely together; their electron clouds can be shaped or deformed by external forces. If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behaviour may be verified by a simple stress-strain test. There are three principal ways in which a load may be applied; tension, compression, and shear.

The stress and strain take different forms, but they are proportional to each other. The constant of proportionality is called the modulus of elasticity or Young's modulus (η). Thus

$$\eta = \frac{\text{stress}}{\text{strain}} \tag{20}$$

Figure (1) shows the relationship between stress and strain for a substantial portion of the range of applied stresses, the stress-strain curve is linear and equation (20) applies, with a constant η (corresponding to the linear region of figure 1). As the stress continues to increase, the stress-strain relationship may become nonlinear, but the material remains elastic; that if the stress is removed the specimen returns to its original dimensions. If the stress is increased beyond the breaking point of the material, the specimen becomes permanently changed and does not recover its original dimensions when the stress is removed.

For simple stretching or compression, the stress is defined as F/A, a quantity that is proportional to the force causing the deformation, where F is the external force and A is the cross-sectional area. The strain, is a measure of the degree of deformation. It is represented by the dimensionless quantity $\Delta L/L$, where ΔL is change in length and L is the origional length. With there definitions, equation (20) becomes

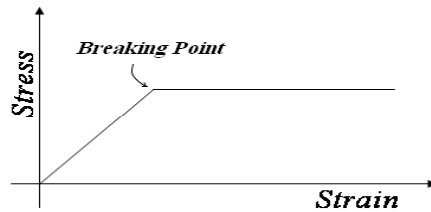$$\frac{F}{A} = \eta \frac{\Delta L}{L} \tag{21}$$

Figure 1: Stress versus Strain Curve

Experiment

The setup on your screen consists of an unstressed rod in red color and the stressed rod (after appling an external force) in violet. Stress-strain figure is, also, shown.

In the control window the default parameters are the external force, Young's modulus, radius, unstressed length and the change in length are $0.4N$, $1 \times 10^6 Pa$, $0.001m$, $0.1m$ and $0.0127m$, respectively.

The student can change the force and radius of the rod. This will change the stress. Changing the length of the rod, the strain will change. Also, the change in Young's modulus will change the strain, and the linear part of the figure will change slope. See the breaking point on the stress-strain figure.

Procedure:

1. Click on the "run" button and start to increase the applied force. What happens to the stress (why)? What happens to the strain (why)? Have you arrived at the breaking point?

2. Set your experiment to the default parameters, then change the radius of the rod while running the experiment. What happens to the stress (why)? What happens to the strain (why)? Have you arrived at the breaking point?

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3. To make a real experiment choose one of the metals from table (1) and use Young modulus for that metal to do the experiment. Fill the table and use "*origin*" to obtain Young modulus from the force versus ΔL graph. Compare your result with that in the control window.

   Note: Recall the linear fitting of your data to find Young modulus.

Table 1: Young Modulus for some metals

Metal	Young Modulus ($1 \times 10^9 Pa$)
Magnesium	45
Aluminum	69
Brass	97
Titanium	107
Copper	110
Nickel	207
Steel	207
Tungsten	407

4 Fluid Dynamics

In this section we have three experiments, buoyancy in static fluid, continuous flow (non viscous flow) and viscous flow.

4.1 Buoyancy in Static Fluids

Theory

We consider a static fluid in a container. Pressure at a point inside the fluid increases with increasing the depth. The fluid exerts on the object a buoyant force $\vec{B}$ directed upwards.

Archimedes principle states that **"Any object completly or partially submerged in a fluid, is buoyed up by a force that is equal to the weight of the fluid displaced by the object"**.

Objects submerged in fluids are buoyed out by a force $\vec{B}$ that is equal to the weight of the displaced fluid, i.e.

$$\vec{B} = m_{fluid}\, \vec{g} = \rho'\, V'\, \vec{g}, \tag{22}$$

where V' is the volume of the submerged part of the object, which is equal to the volume of the displaced fluid and ρ' the density of the fluid. At ststic equilibrium, the net force exerted on the floating object in the vertical direction is zero, i.e.

$$W = B \tag{23}$$

where $W = m_{obj}g = \rho g V$, ρ is the density of the object, V the volume of the object. This leads to

$$\frac{V'}{V} = \frac{\rho}{\rho'} \tag{24}$$

Note $V' < V$ implies $\rho < \rho'$.

Experiment

The setup on your computer screen consists of a ball submerged in a fluid with the following default parameters for the sphere radius, sphere density and fluid density, respectively; $2cm$, $0.8g/cm^3$ and $1g/cm^3$.

Table 2: Density

Material	Density (kg/m^3)
Interstellar space	10^{-20}
Air	1.21
Wood	525
Ice	917
Water	998
Sea water	1024
Polystyrene	1050
Whole blood	1060
Glass	2190
Aluminum	2710
Iron	7800
Mercury	13600

Note: The temperature of air, water and sea water is $20°C$.

Procedure:

1. Run the experiment with the default numbers. Explain the oscillatory motion of the ball and explain why the ball is partially submerged.

2. Set the value of ρ_{obj} to be equal to ρ_f and repeat the experiment. What do you find? Explain what you find.

3. Set the value of ρ_{obj} to be larger than ρ_f and repeat the experiment. What do you find? Explain what you find.

4. Change the density of the object or the liquid as described in the manual to observe how the object is buoyed out.

5. Choose values for ρ_f, ρ_{obj}, sphere radius and calculate the buoyancy force for the values you have choosen. Plot a graph between time and buoyancy force then compare it with value in the graph for an object in equilibrium.

6. Find the weight of the object in vacuum.

7. Find the weight of the object in the liquid.

4.2 Continuous Flow

Theory

In this experiment, we consider the flow of a nonviscous fluid in a tube with a variable cross-section. The fluid is in a steady state flow (not turbulent flow).

A volume of ΔV of the fluid passes a cross-section (A) with velocity (v) in the time interval (Δt). For an incompressible fluid, $A_1 v_1 \Delta t = A_2 v_2 \Delta t$

$$A_1 v_1 \Delta t = A_2 v_2 \Delta t \tag{25}$$
$$\Rightarrow A_1 v_1 = A_2 v_2 \tag{26}$$

Note if $A_1 < A_2$, then $v_1 > v_2$.

Experiment

The setup on your computer screen consists of a tube with cross-sections 1 and 2. In the control window the default parameters take the following values, respectively; radius1, radius2, velocity1 and velocity2 are $0.03m$, $0.1m$, $0.06m/s$ and $0.0054m/s$.

Procedure:

1. Click the "run" button and observe the change in the velocity while you change one of the two radii. What is your conclusion?

2. (a) Calculate the volume rate of flow for the parameters radius1 $= 3cm$, radius2 $= 10cm$, velocity1 $= 0.35m/s$ and velocity2 $= 0.0315m/s$.

   (b) Plot the volume rate of flow versus time for the previous parameters.

3. From step 2, find the volume of the fluid that passes through the tube in $3\ minutes$.

4.3 Viscous Flow

Theory

In this experiment we consider the viscous flow. Take for example the flow of honey on the spoon. In this kind of flow of a fluid in a pipe, the fluid sticks to the inner wall of the pipe. The adhesive force depends on the distance of a volume element of the fluid from the pipe wall. The fluid flows when there is a pressure difference in the pipe.

Consider a horizontal plate with an area 'A', where a viscouse fluid is flowing on. We can define the stress on the fluid to be F/A, where A is the area of the layer of fluid. A fluid responds through a change in speed v across each layer. The ratio between stress and strain in the fluid is called the coefficient of viscosity η of the fluid

$$\eta = \frac{F/A}{v/d} = \frac{Fd}{vA} \tag{27}$$

For a volume element a distance 'd' for the plate to flow with velocity 'v', a force 'F' is needed where

$$F = \eta \frac{vA}{d} \tag{28}$$

The SI unit for viscosity is the $N.s/m^2$. Table (3) contains the viscosity coefficient for some selected fluids.

A practical application of viscosity occurs in the fluid flow mostly through cylindrical pipes. In the case of a cylindrical pipe, the variation of the velocity with location across the pipe is not linear. Assuming that the central layer moves at speed v and the layer next to the wall is at rest, the velocity in a cylindrical shell of radius r can be written as

$$v = v_0(1 - \frac{r^2}{R^2}), \tag{29}$$

where v_0 is the central velocity represented by

$$v_0 = \frac{\Delta p R^2}{4\eta L}, \tag{30}$$

where $\frac{\Delta p}{L}$ is the pressure gradiant of the fluid, 'R' the radius of the cylinder and 'r' the radius of the shell ($0 \leq r \leq R$). By considering the flow through

the whole cylinder, the volume rate of flow $\frac{\Delta V}{\Delta t}$ is

$$\frac{\Delta V}{\Delta t} = \frac{\pi R^4}{8\eta} \frac{\Delta p}{L} \qquad (31)$$

This applies for laminar flow where υ is sufficiently small.

Table 3: Viscosity of some fluids

Fluid	Viscosity $(N.s/m^2)$
Motor oil at $20^o C$	0.03
Glycerine at $20^o C$	1.5
Blood at $37^o C$	4×10^{-3}
Water at $20^o C$	1×10^{-3}
Water at $90^o C$	0.32×10^{-3}
Gasoline at $20^o C$	2.9×10^{-4}
Air at $20^o C$	1.8×10^{-5}

Experiment

The setup on your screen consists of a fluid flowing through a tube. In the control window the default parameters the pressure gradiant, density, viscosity and radius are $0.5N/m^3$, $998kg/m^3$, $0.001N.s/m^2$ and $0.01m$, respectively.

Procedure:

1. For the default numbers, calculate the center velocity. Plot the center velocity versus time graph and compare it with the calculating value.

2. Change the pressure gradiant. What happens to the velocity? Explain your result.

3. Change the viscosity. What happens to the center velocity? Explain your result.

4. For the default numbers, calculate the volume rate of flow. Plot the volume rate of flow versus time graph and compare it with the calculating result.

5. Change the radius. What happens to the volume rate of flow? Explain your result.

5 Modern Physics

Modern physics began with the beginning of the twentieth century with Max Planck's discovery of the role of energy quantization in blackbody radiation, a revolutionary idea soon followed by Albert Einstien's equally revolutionary theory of relativity and the quantum theory of light. The ideas of modern physics represented totally new directions in thought, and the story of their development is exceptionally interesting. In this set of experiments we describe briefly the blackbody radiation, Bohr model of the atom and Compton effect.

5.1 Blackbody Radiation

Theory

The ability of a body to radiate energy is closely related to its ability to absorb radiation. It is convenient to consider, as an ideal black body, one that absorbs all radiation incident upon it, regardless of frequency. In laboratory a blackbody can be approximated by a hollow object with a very small hole leading to its interior (the physical blackbody is the small whole). Any radiation striking the hole enters the cavity, where it is trapped by reflection back and forth until it is absorbed inside the cavity with almost no change to escape out again.

The spectral radiancy $R(\lambda, T)$ tells us how the intensity of radiation from the blackbody varies with wavelength for a given temperature. In other words, it is the radiated power per unit area per a specific wavelength ($W/m^2.m$). We can find the radiant intensity $I(T)$ for any temperature by adding up the spectral radiancy over the complete range of wavelengths. Thus

$$I(T) = \int_0^\infty R(\lambda, T)d\lambda, \tag{32}$$

where $I(T)$ (measured in units of W/m^2) is the total radiated power per unit area of the cavity. This equation shows that the radiant intensity $I(T)$ can be interpreted as the area under the spectral radiancy curve in figure (2).

Blackbody theory occupied physicists for about 20 years before the begining of the twentieth century. The history of development of its theory will be discussed briefly;
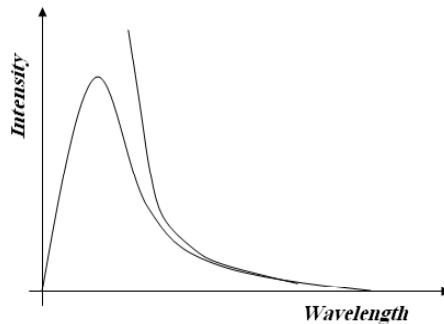
Figure 2: Radiancy Curve

Stefan-Boltzmann law: The radiant intensity is related to the temperature by

$$I(T) = \sigma \mathrm{T}^4,\tag{33}$$

where σ $(= 5.57 \times 10^{-8}\ W/m^2.K^4)$ is the Stefan-Boltzmann constant.

Wein's law: The wavelength at which the spectral energy density curve has a maximum (λ_{max}) varies as $1/T$ and the product $\lambda_{max}T$ is a universal constant. Its meaured value is

$$\lambda_{max}T = 2.898 \times 10^{-3}\mathrm{m.K}\tag{34}$$

Wien's displacement law quantitavely expresses the empirical fact that the peak in the blackbody spectrum shifts to shorter wavelengths (higher frequancies) as the temperature is increased.

Rayleigh-Jeans formula: The classical formula for the radiancy of a blackbody is given by

$$R(\lambda, T) = \frac{2\pi c k_\mathrm{B} \mathrm{T}}{\lambda^4}\tag{35}$$

This formula is in reasonable agreement with experimental data at large wavelengths. At short wavelengths, major disagreement appears; as $\lambda \to 0$,

$R(\lambda, T)$ blows up. This is called the ultraviolet catastrophe.

Max Planck's Solution to the Ultraviolet Catastrophe: In 1900, Max Planck derived a formula for a blackbody radiation that is in complete agreement with experiment at all wavelenghts. This formula is

$$R(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{\lambda k_B T}} - 1)}, \tag{36}$$

where h $(= 6.626 \times 10^{-34} J.s)$ is Planck constant.

Experiment

The setup on your screen consists of an object that changes its color depending on it's temperature (the default temperature (T) is $1.1 \times 10^3 K$). Also, a spectral intensity versus wavelength graph is found there. On the right hand side of your screen, you can see the spectral intensity peaks wavelengths, the emission peaks region, the peak spectral intensity (radiancy $R(\lambda, T)$), and the integrated intensity (radiant intensity $I(\lambda, T)$).

Procedure:

1. Change the temperature and observe the change in the radiancy curve and the color of the object.

2. Choose a value for the temperature and record the corresponding integrated intensity. Doubled the temperature and calculate the new integrated intensity. Compare the ratios $T_1 : T_2$ and $I_1 : I_2$. Explain the results.

3. Find the corresponding temperature for each visible color in table (4) by changing the value of the temperature in the control window and observing the radiated colour.

4. Plot the radiancy versus wavelength, using origin, for at least 10 different wavelengths scanning the region $\lambda \, \epsilon \, (0, 10000 \mathring{A})$. Explain your graph.

Table 4: Visible colours wavelengths

Color	Wavelength ($\mathring{A}$)
Red	6500
Orange	5900
Yellow	5700
Green	5100
Blue	4750
Indiga	4450
Violet	4000

5.2 Bohr Atom

Theory

Most of our knowledge about atoms, molecules, and nuclei comes from studying the radiation emitted or absorbed by them. A spectrum of atomic hydrogen in the visible region had been measured with great precision in the late 1800s, and its interpretation was puzzling for scientists.

An empirical formula for the wavelengths of the lines of atomic hydrogen was developed in 1885 by Balmer. The general formula for the wavelengths of the lines of atomic hydrogen is

$$\frac{1}{\lambda} = R \left(\frac{1}{m^2} - \frac{1}{n^2}\right), \quad n = 3, 4, 5, ..., \tag{37}$$

where R $(= 1.097 \times 10^7 m^{-1})$ is the Rydberg constant, $m = 2$ for the Balmer series of hydrogen in the visible region. Soon, researchers turned up series in the infrared region corresponding to $m = 3$, $m = 4$ and $m = 5$, which are called Pashen, Brackett and Pfund series, respectively. Another series in the ultraviolet region with $m = 1$ is called Lyman series.

The key to understanding the above empirical formula was provided by the model devrloped by Bohr in 1913, who considered three postulates;

1. The hydrogen atom can exist for a long time without radiating it's energy and eventually collapsing, *i.e.* electrons exist in stationary states.

2. The hydrogen atom can emit or absorb radiation only when the atom changes from one of its stationary states to another. The energy of the emitted (or absorbed) photon is equal to the difference in energy between the two states.

3. Electrons orbit atoms in levels to have angular momenta such that

$$L = n\bar{h}, \tag{38}$$

where n is an integer.

To study the electron motion about the nucleus, we combine Coulomb's force law with Newton's second law of motion for an object travelling in a circular motion, *i.e.*

$$\frac{1}{4\pi\epsilon_0} \frac{(Ze)(e)}{r^2} = m_e \frac{v^2}{r}, \tag{39}$$

where Z is the atomic number, $Z = 1$ identifying hydrogen, m_e is the mass of the electron, and v is the speed of the electron in its orbit. Solving equation (39) for v yields

$$v(r) = \sqrt{\frac{ze^2}{4\pi\epsilon_0 m_e r}} \tag{40}$$

The kinetic and potential energies are given, respectively, by

$$K(r) = \frac{1}{2}m_e v^2 = \frac{ze^2}{8\pi\epsilon_0 r} \tag{41}$$

$$U(r) = -\frac{ze^2}{4\pi\epsilon_0 r}, \tag{42}$$

and the total mechanical energy $E(r)$ becomes

$$E(r) = K(r) + U(r) = -\frac{ze^2}{8\pi\epsilon_0 r} \tag{43}$$

The angular momentum follows directly using equation (40)

$$L(r) = m_e v r = \sqrt{\frac{ze^2 r m_e}{4\pi\epsilon_0}} \tag{44}$$

Now, we can equalize equation (44) and equation (38) and solve them for the orbit radius r_n. We find

$$r_n = (\frac{\epsilon_0 h^2}{ze^2\pi m_e})n^2 = \frac{n^2}{z}a_0, \quad n = 1, 2, 3, ..., \tag{45}$$

where a_0 ($= 5.292 \times 10^{-11} = 0.529\text{Å}$) is the radius of the Bohr orbit corresponding to $n = 1$, which is the ground state of the hydrogen atom.

The energy expression for stationary states comes by substituting equation (45) into equation (43);

$$E_n = -\frac{z^2 e^4 m_e}{8\epsilon_0^2 h^2}n^2 = \frac{z^2}{n^2}E_0, \tag{46}$$

where $E_0 = -13.6$ eV the ground state energy of a hydrogen atom, $i.e.$ $n = 1$ and $z = 1$.

In 1924, de Broglie gave a satisfying physical interpretation of the Bohr rule for the quantization of angular momentum; if we represent the circulating electron in terms of its de Broglie wave, then the stationary states are those in which the electron's de Broglie wave joins onto itself with the same phase after each revolution. The de Broglie wavelength must fit around the circumference of the orbit an integral mumber of times, or simply

$$n\lambda = 2\pi r, \quad n = 1, 2, 3, ..., \tag{47}$$

Experiment

The setup on your screen shows a single electron atom with its energy levels. The default numbers for the quantum number and number of protons are 3 and 1, respectively.

Procedure:

1. Consider the hydrogen atom $(z = 1)$ and change the quamtum number for the electron (the orbit number of the electron). What is the relation between the electron energy (E_n) and the quantum number (n)?

2. Fix the quantum number to $n = 3$ and change z observing the electron energy. What is the relation between the electron energy and the number of protons? Explain your result.

3. Repeat step 1 observing the radius of electron orbits for the hydrogen atom $(z = 1)$. What is the relation between the radius and the quantum number?

4. Repeat step 2 observing the radius of electron orbits for an electron at the ground state $(n = 1)$. What is the relation between the radius of the ground state and the number of protons? Explain your result.

5. For each of Lyman, Balmer and Pashen series. Plot a graph for the energy levels choosing at least 3 orbits. What can you say about the energy difference between successive orbits for each series?

5.3 Compton Effect

Theory

Compton effect is the scattering of radiation from atoms, where light behaves like particles. The Compton effect can readily be understood in terms of collisions between photons and particles.

In Compton effect, a photon with energy E and wavelength λ falls on a static particle, and a photon with wavelength λ' will scattered. Since the incident photon transfers some of its energy to the particle it collides with, the scattered photon must have a lower energy E' (lower frequency ν', larger wavelength λ').

We now apply the law of conservation of energy to this collision; Since the recoil particle may have a speed that is comparable with that of light, we must use the relativistic expression for the conservation of energy, namely;

$$h\nu + mc^2 = h\nu' + mc^2 + K, \qquad (48)$$

where mc^2 is the rest energy of the particle and K $(= \sqrt{m^2c^4 + c^2P'^2_{particle}})$ is its relativistic kinetic energy.

Also, applying the law of conservation of linear momentum to the collision gives

$$\vec{P}_{photon} = \vec{P}'_{photon} + \vec{P}'_{particle} \qquad (49)$$

Carrying out the necessary algebraic steps in equations (48) and (49) leads to the simple result for the shift in wavelength of the scattered photon in terms of the scattering angle of the photons (ϕ), and the mass of the target, namely;

$$\Delta\lambda = \lambda' - \lambda = \lambda_{Comp}(1 - \cos\phi), \qquad (50)$$

where λ_{Comp} is the Compton wavelength of the scattering particle given by

$$\lambda_{Comp} = \frac{hc}{mc^2} \qquad (51)$$

Experiment

The setup on your screen consists of two objects representing the electron and the photon. You can display the photon wave from the "*display*" button. In the control window the default parameters for the photon deflection, initial wavelength, particle mass, wavelength change and Compton wavelength are $54°$, $2.43 \times 10^{-12}m$, $9.11 \times 10^{-31}kg$, $1 \times 10^{-12}m$ and $2.43 \times 10^{-12}m$, respectively.

Procedure:

1. Change the angle of scattering and observe the change in wavelength shift.

   (a) Determine the angle of the maximum and minimum wavelength shift.

   (b) Find the angle,where the wavelength shift equals the Compton wavelength.

   (c) Determine which photon energy is larger? The energy of the scattered photon or the incident photon?

2. From the above theory answer the following for default parameters.

   (a) Determine the energy of the photon before and after collision.

   (b) Determine the energy of the electron before and after collision.

   (c) What happens to the photon energy during collision?

   (d) What happens to the electron energy during collision?

   (e) Determine the total energy of the system before collision.

   (f) Determine the total energy of the system after collision.

   (g) What happens to the total energy during collision?

3. From the energy graphs answer the following for default parameters.

   (a) Determine the energy of the photon before and after collision.

   (b) Determine the energy of the electron before and after collision.

   (c) What happens to the photon energy during collision?

   (d) What happens to the electron energy during collision?

   (e) Determine the total energy of the system before collision.

(f) Determine the total energy of the system after collision.

(g) What happens to the total energy during collision?

4. Compare the corresponding results in steps (2) and (3).

5. (a) Consider a particle of a mass $m_e/2$. Find the Compton wavelength for such a particle and compare it with λ_{Comp} for the electron.

   (b) Repeat step (5.a) for a particle of mass $2m_e$. What do you conclude?

   (c) What do you conclude from (5.a) and (5.b)?