Module 4

Modern physics

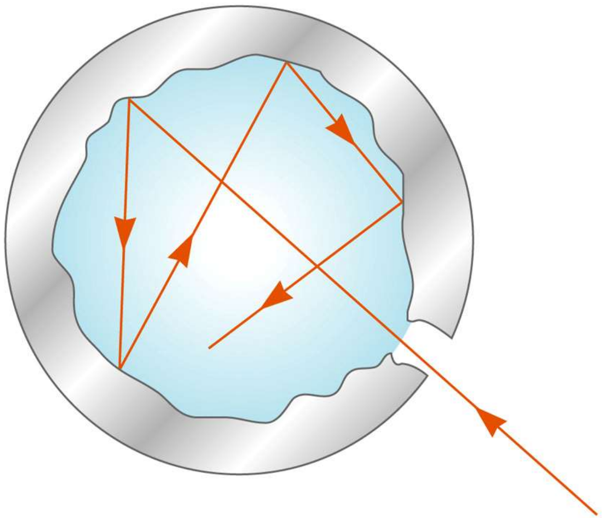
1. Blackbody Radiation and Planck's Hypothesis

Thermal radiation

- An object at any temperature emits electromagnetic radiation called thermal radiation.
- The spectrum of the radiation depends on the temperature and properties of the object.
- From a classical point of view, thermal radiation originates from accelerated charged particles near the surface of an object.

Blackbody

- Is an ideal system that absorbs all radiation incident on it.
- An opening in the cavity of a body is a good approximation of a blackbody.



1. Blackbody Radiation and Planck's Hypothesis

❑ Blackbody radiation (1)

• The nature of the blackbody radiation depends only on the temperature of the body, not on the material composition of the object.

• The distribution of energy in blackbody radiation varies with wavelength and temperature.

- The total amount of energy (area under the curve) it emits increase with the temperature.

1. Blackbody Radiation and Planck's Hypothesis

Stefan-Boltzmann Law

- Joseph Stefan (1879)– total radiation emission per unit time & area over all wavelengths and in all directions:

$$E_b = \sigma T^4 \ \left(\mathrm{W/m^2}\right)$$

σ=Stefan-Boltzmann constant

=5.67 $\times 10^{-8}$ $\mathrm{W/m^2K^4}$

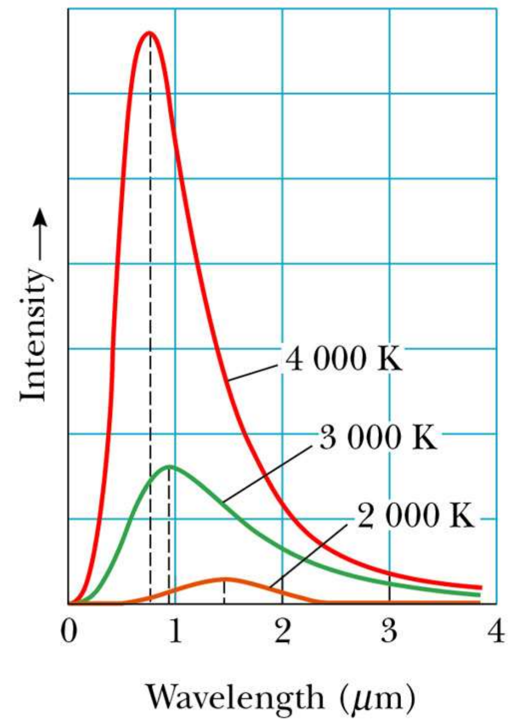
T must be in absolute scale.

1. Blackbody Radiation and Planck's Hypothesis

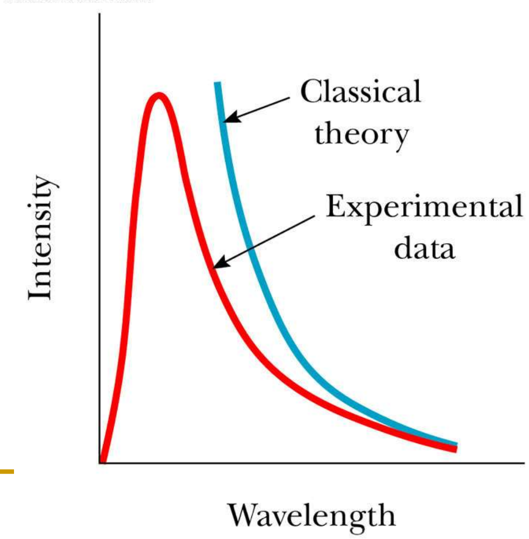
❑ Blackbody radiation (2)

- The peak of the distribution shifts to shorter wavelengths. This shift obeys Wien's displacement law:

$$\lambda_{max} T = 0.2898 \times 10^{-2} \text{ m} \cdot \text{K}$$



- The classical theory of thermal radiation at the end of 19th century failed to explain the distribution of energy of the blackbody radiation.



1. Blackbody Radiation and Planck's Hypothesis

Planck's hypothesis

- To solve the discrepancy between the classical physics prediction and the observation of the blackbody radiation spectrum, in 1900 Planck developed a formula for the spectrum that explains the observed spectrum behavior.
- Planck's hypothesis:

  - Blackbody radiation is produced by submicroscopic charged oscillation (resonators).

  - The resonators are allowed to have only certain discrete energies given by:

$$E_n = nhf$$

n= quantum number (positive integer)

f = frequency of vibration of the resonators

h= Planck's constant 6.626 x 10^{-34} J s

- Energy is quantized.
- each discrete energy value represents a different quantum state, where the quantum number n specifies the quantum state.

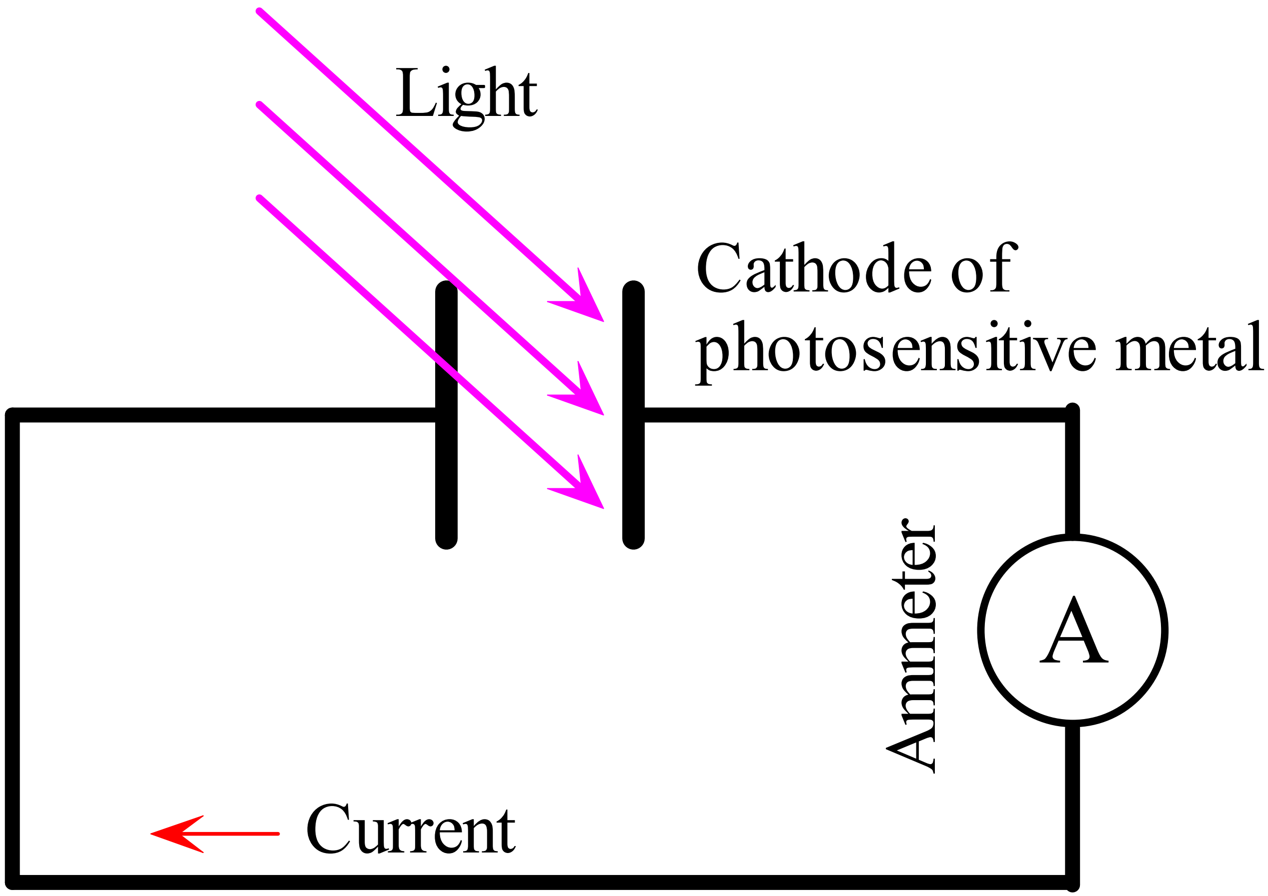
2. Photoelectric Effect and Particle Theory of Light

History

- After Young's experiment with interference (1830), light was understood to be a wave.
- Most physicists accepted the wave nature of light
- Hertz, a student of Kirchoff, discovered the Photoelectric effect in 1686.
- Could not explain it and went on to discover other things, like how to produce radio waves

2. Photoelectric Effect and Particle Theory of Light

The Experiment



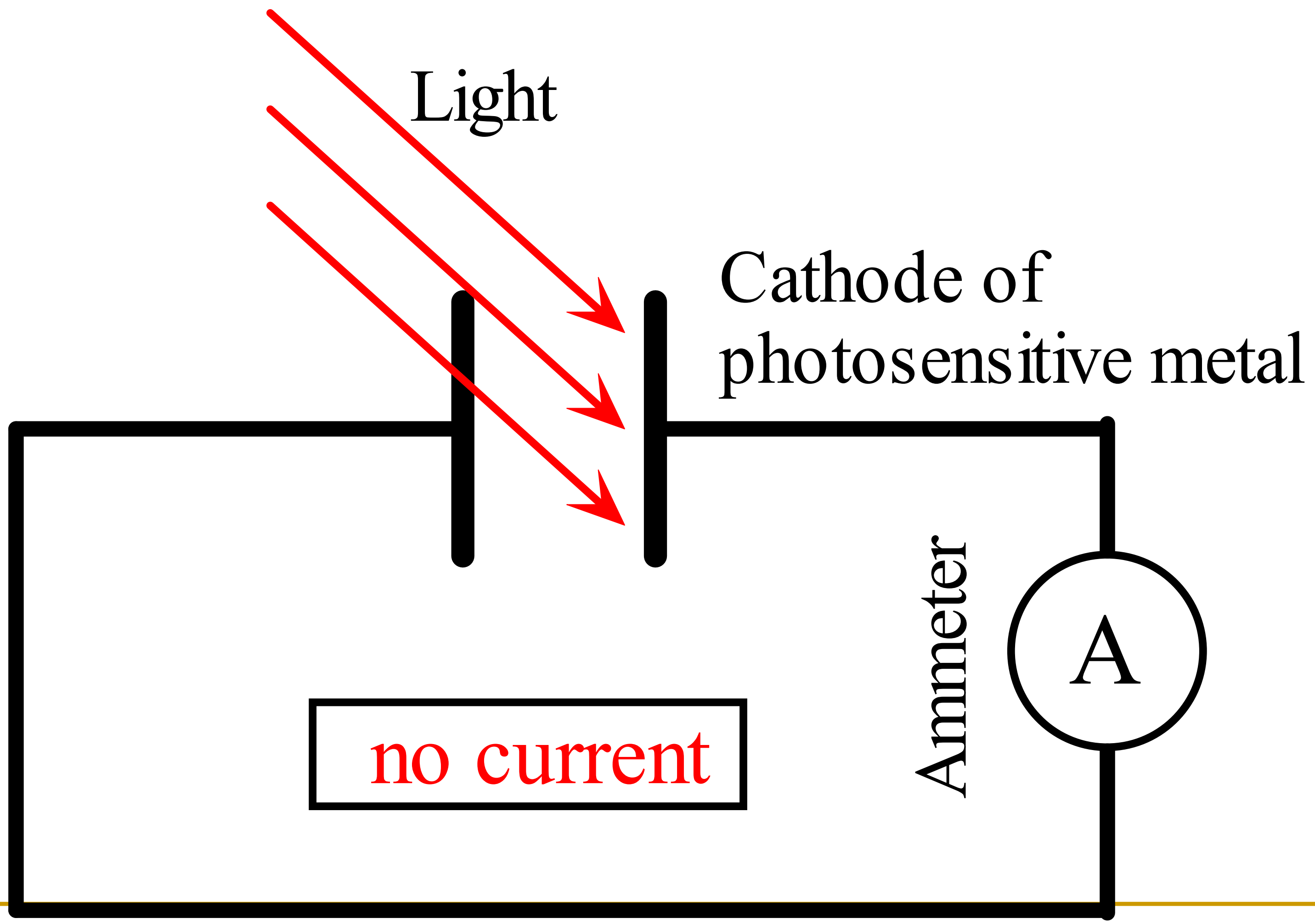
2. Photoelectric Effect and Particle Theory of Light

The Experiment

- Shining violet light on the cathode caused a current to flow.
- Electrons were being ejected
- Increasing the intensity of light caused the current to increase

2. Photoelectric Effect and Particle Theory of Light

The Experiment



2. Photoelectric Effect and Particle Theory of Light

The Experiment, Part II

- Shining red light on the cathode <u>caused no current</u> to flow.
- Increasing the intensity of light had no effect!

2. Photoelectric Effect and Particle Theory of Light

The Problem

- If light was a wave, then the energy it would deliver to the electrons (to knock them off the metal) depended on its intensity, not it's frequency
- But the electrons in the Photoelectric experiment were sensitive to the frequency!
- No matter how intense, red light could not cause any electrons to flow.
- Even very low intensity violet light caused some electrons to be ejected.

2. Photoelectric Effect and Particle Theory of Light

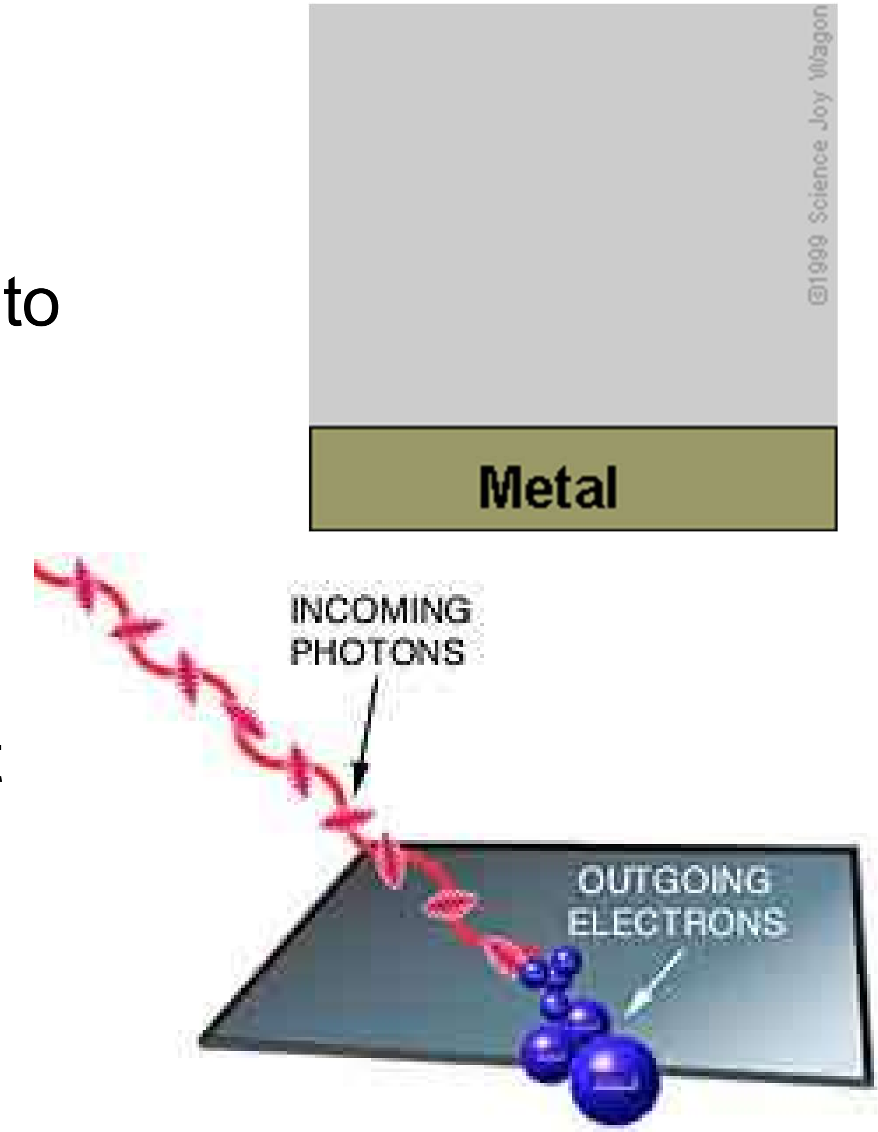
The Solution

- Proposed by Einstein in 1905
- Light must be a particle
- The energy of the particle must be related to it’s frequency
- This connected with earlier work of Max Planck

2. Photoelectric Effect and Particle Theory of Light

The Solution

- Electrons needed a certain amount of energy to be freed from the metal. Something has to do work on them to free them.
- This energy debt is called the work function
- Light particles that did not have that minimum energy would not eject electrons, no matter how many particles there were.



2. Photoelectric Effect and Particle Theory of Light

Theory

- The energy of light is quantized and related to it's frequency

$$E = h \cdot f$$

$$h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$$

2. Photoelectric Effect and Particle Theory of Light

Example Problem

- What is the energy associated with a photon with a wavelength of 632 nm?

$$f = \frac{c}{\lambda} \text{ and } E = h \cdot f$$

$$E = h \cdot \frac{c}{\lambda} = \frac{\left(6.626 \times 10^{-34}\ \text{J} \cdot \text{s}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}{\left(632 \times 10^{-9}\ \text{m}\right)}$$

$$E = 3.14 \times 10^{-19}\ \text{J}$$

2. Photoelectric Effect and Particle Theory of Light

Theory

- The KE of the ejected electron is given by

$$KE = h \cdot f - \phi$$

Energy of electron (KE)

Energy of incident light ($h \cdot f$)

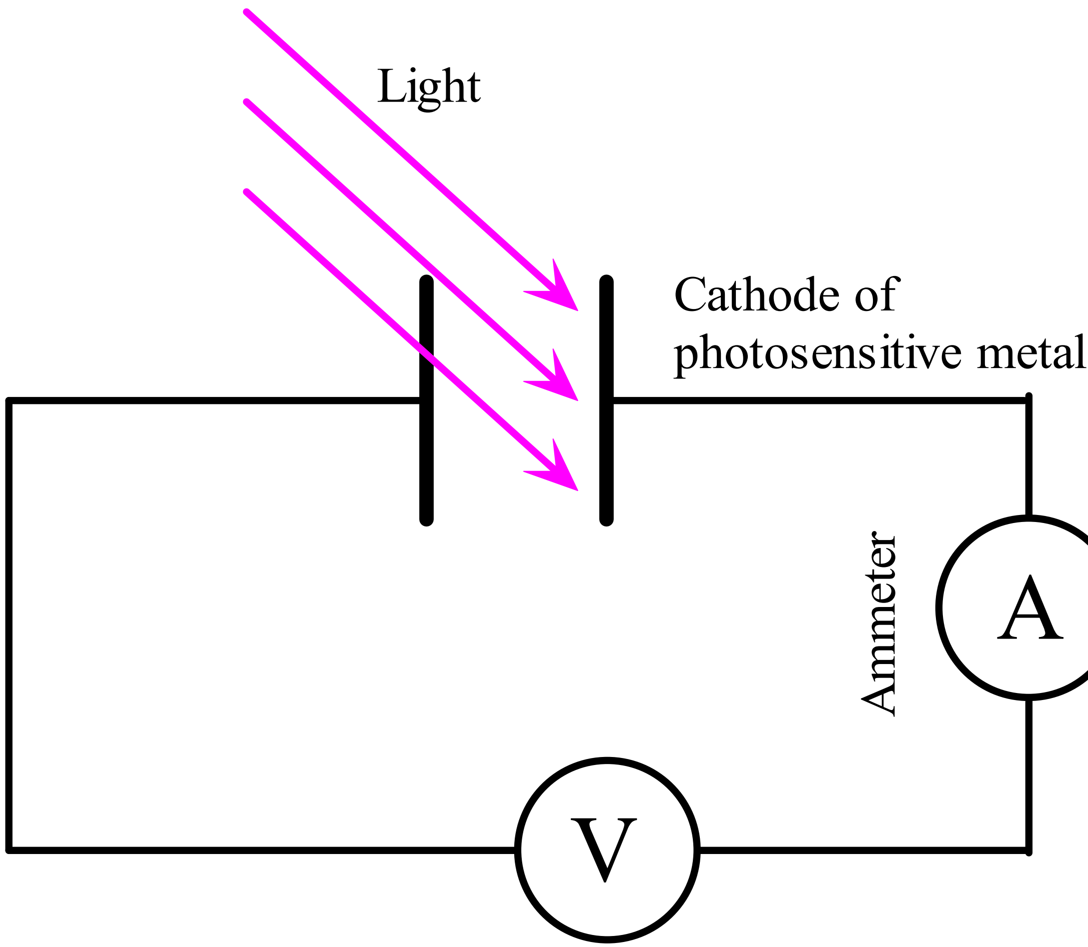
Energy to eject electron (ϕ)

$$\phi = \text{work function}$$

- The work function depends only on the metal.
- It is the energy debt of the bound electrons.

2. Photoelectric Effect and Particle Theory of Light

Experimental Details



2. Photoelectric Effect and Particle Theory of Light

Theory

- With enough voltage V_o, the ejected electrons can be stopped.

$$KE = eV_0$$

$$eV_0 = h \cdot f - \phi$$

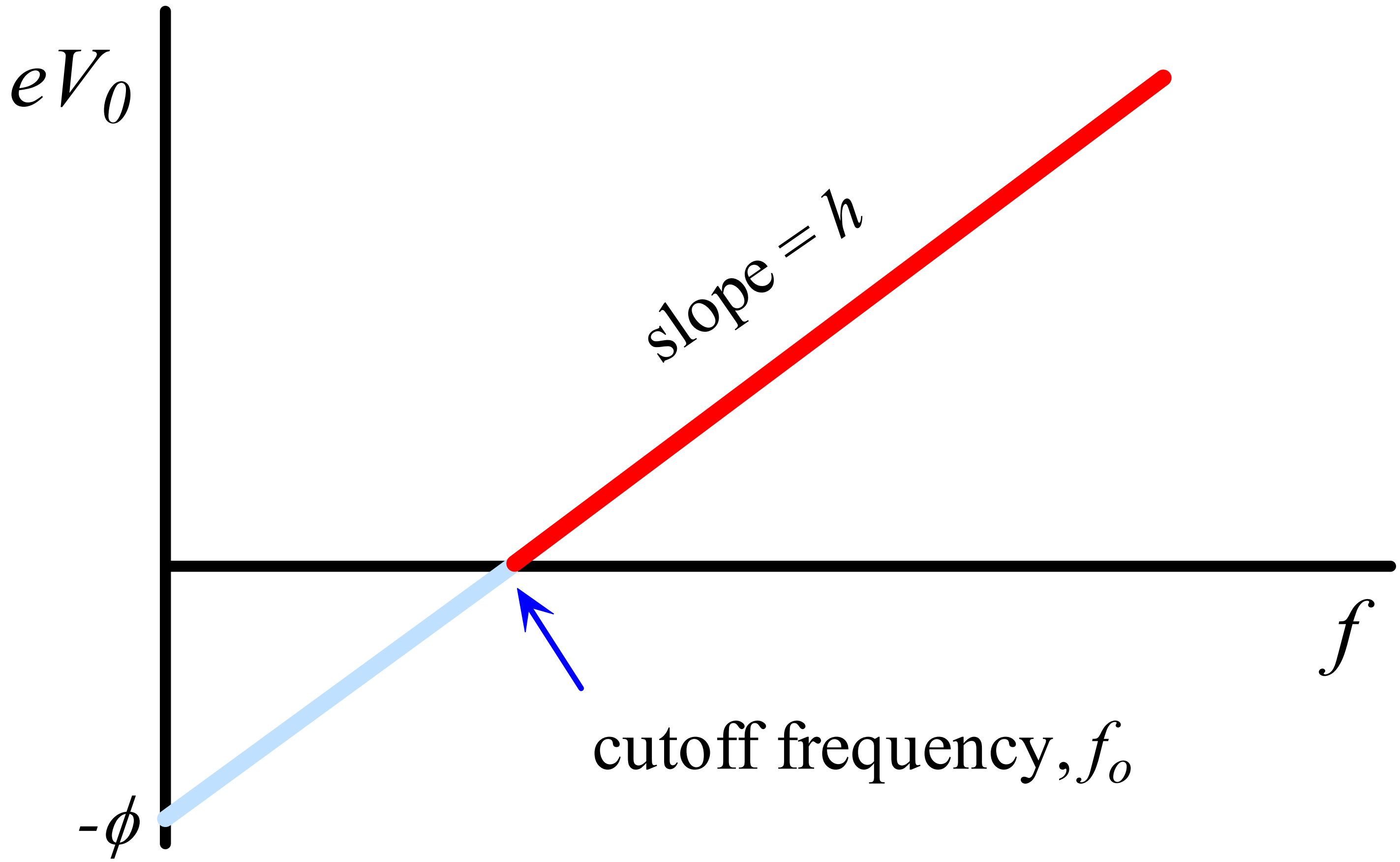
2. Photoelectric Effect and Particle Theory of Light

Experiment

- Using the simulator, start with Sodium and set the voltage to 0 V.
- Determine the minimum frequency of the incident light that is needed to eject electrons.
- For each frequency that will eject electrons, measure and plot the voltage needed to then stop the current.
- Make a graph of the stopping potential (J) vs. the frequency of light. Find the slope and the intercept of the graph.

2. Photoelectric Effect and Particle Theory of Light

Prediction



2. Photoelectric Effect and Particle Theory of Light

Confirmation

- Robert Millikan (1910) performed careful experiments that completely verified Einstein's theory.
- Einstein was awarded the Nobel Prize for this theory

2. Photoelectric Effect and Particle Theory of Light

Units of Energy

- Recall that energy can also be measured in electron volts.

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

- Planck's constant can be written in terms of eV

$$h = 4.14 \times 10^{-15}\ \text{eV} \cdot \text{s}$$

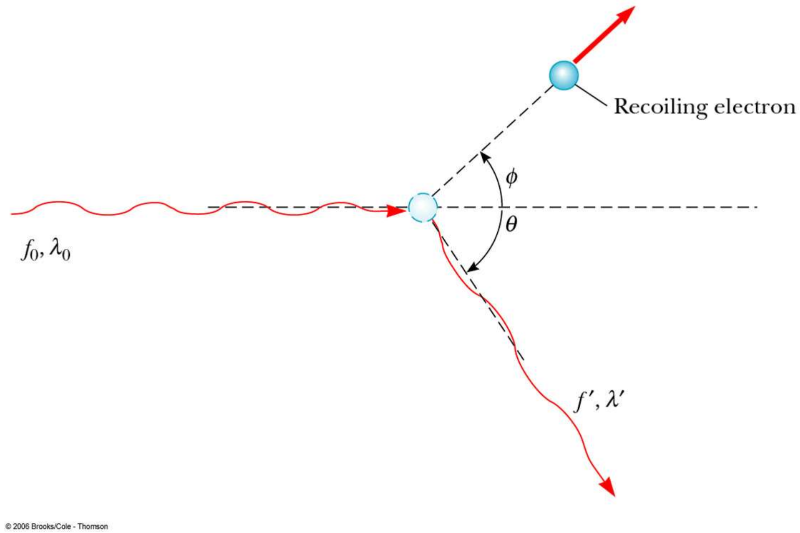
2. Photoelectric Effect and Particle Theory of Light

Example

- The work function for a metal is 3.4 eV. What is the threshold frequency f_o needed to produce photoelectrons from this metal?
- $f = 8.21 \times 10^{14}$ Hz

3. Compton Effect

- Photon nature of light
  - Compton's experiment:



- X-ray beam of wavelength λ_0 directed to a lock of graphite.
- Compton observed that the scattered x-rays had a slightly longer wavelength (lower energy).

Compton shift $\Delta\lambda = \lambda' - \lambda_0$

- The amount of reduction in energy depends on the amount of angle x-rays are deflected.

3. Compton Effect

- Compton's explanation :

  - If a photon behaves like a particle, its collision with other particles is similar to a collision between two billiard balls.
  - A photon collides with an electron at rest and transfer part of its energy and momentum to the electron. Then from conservation of energy and momentum he derived a formula:

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

$h/m_e c$ = 0.00243 nm Compton wavelength

m_e:electron mass
θ: scattering angle

3. Compton Effect

❑ Example: Scattering x-rays

- X-rays of wavelength λ_0 =0.200000 nm are scattered from a block of material. The scattered x-rays are observed at an angle of 45.0° to the incident beam.

  (a) Calculate the wavelength of the scattered x-rays at this angle.

$$\Delta\lambda = \frac{h}{m_e c}(1-\cos\theta) = \frac{6.63\times10^{-34}\ \mathrm{J\cdot s}}{(9.11\times10^{-31}\ \mathrm{kg})(3.00\times10^{8}\ \mathrm{m/s})}(1-\cos 45.0°) = 7.11\times10^{-13}\ \mathrm{m}$$

$$\lambda = \Delta\lambda + \lambda_0 = 0.200711\,\mathrm{nm}$$

(b) Compute the fractional change in the energy of a photon in the collision.

$$E = hf = h\frac{c}{\lambda}$$

$$\frac{\Delta E}{E} = \frac{E_f - E_i}{E_i} = \frac{hc/\lambda_f - hc/\lambda_i}{hc/\lambda_i} = -\frac{\Delta\lambda}{\lambda_i} = -\frac{0.000711\,\mathrm{nm}}{0.200711\,\mathrm{nm}} = -3.54\times10^{-3}$$

4. Dual Nature of Light and Matter

❑ Light and electromagnetic radiation

- The photoelectric effect and the Compton scattering suggest particle nature of light with energy hf and momentum h/λ.
- At the same time light behaves like wave.

Light has a dual nature, exhibiting both wave and particle characteristics.

❑ Wave properties of particles

- De Broglie's idea :

All forms of matter have both properties - wave and particle characteristics

- According to de Broglie's idea, electrons like light have a dual particle-wave nature with the following relation among the momentum, energy and wavelength (de Broglie wavelength of a particle) :

$$\lambda = h / p = h / (mv)$$

An application: electron microscope

$$f = E / h$$

- His postulate was verified by diffraction pattern produced by electrons.

Wave Function

- Light and electromagnetic radiation

  - In 1926, Schroedinger proposed a wave equation that described how wave change in space and time : The Schroedinger wave equation
  - Solving Schroedinger's equation determines a quantity Ψ called the wave function.

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\Delta\Psi+U(x,y,z)\Psi$$

  - Putting aside historical controversies over the interpretation of a wave function Ψ , this wave function describes a single particle, the value of $|\Psi|^2$ at some location at a given time is proportional to the probabilities per unit volume of finding the particle at that location at that time.
  - Adding up all the values of $|\Psi|^2$ in a given region gives the probability of finding the particle in that region.