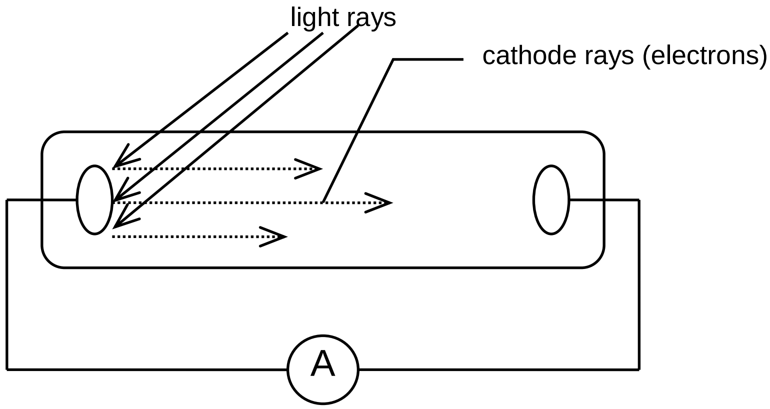
Physics 30 Lesson 29 The Photoelectric Effect

I. Discovery of the photoelectric effect

In 1887, Heinrich Hertz discovered the photoelectric effect while working with a cathode ray tube. Hertz's cathode ray tube was **turned off** and sitting on his lab bench. A high frequency external light source was turned on and light from the external light source was allowed to strike the metal cathode in the cathode ray tube. The result was startling. Cathode rays (i.e. electrons) began to flow from the cathode to the anode even though the tube was not turned on.



Hertz immediately began to test this effect and, since light "photo" caused electric charges "electric" to flow, he called it the **photoelectric effect**. The electrons emitted by the metal surface when illuminated by an external light source are referred to as **photoelectrons.**

Hertz began a thorough examination of the photoelectric effect. His results can be summed up in the following:

1. A substance shows a photoelectric effect only if the incident light has a frequency above a certain **threshold** value known as the **threshold frequency** (f_o). Zinc, for example, will emit electrons for violet light but not for blue light.
2. Any frequency below the threshold value will not produce a stream of photoelectrons off the metal surface.
3. Different metal surfaces (i.e. silver versus copper) have different threshold frequency values.
4. Once the external light is at or above the minimum threshold frequency, photoelectric current flow is instantaneous**.**
5. Increasing the frequency of the incident light does **not** affect the photoelectric current flow (i.e. the frequency does not affect the number of electrons being emitted).
6. Increasing the **intensity** of the external light (i.e. using a brighter light source) caused an increase in the amount of photoelectric flow (called the **photocurrent**) through the tube. In short, the **photocurrent** is proportional to the **intensity** of the external light source.
7. Finally, Hertz discovered that increasing the external light source's **frequency** caused the **kinetic energy** of the photoelectrons to increase. In other words, the speed of the electrons increased with higher energy light.

How do we explain these results? From the **classical physics point of view**, where light is an electromagnetic wave, when light is illuminated on the surface of a metal, electrons in the metal are violently shaken and oscillated by the vibrating electromagnetic field of the light. If the oscillation is too great to keep the electrons inside the metal, they jump out of the metal surface. According to the classical theory, the energy given to the electrons is proportional to the square of the strength of the electromagnetic field. Hence the maximum energy of the photoelectron must be dependent on the intensity of the light illuminated which completely contradicts Hertz's experimental results. Results (1), (2), (5) and (7) above can never be explained with the classical theory. Thus, it is impossible to explain Hertz's results within the classical theory consisting of Newtonian mechanics and Maxwellian electromagnetism.

From a **quantum physics point of view**, we can understand the photoelectric effect without contradiction if we think that light is instantaneously absorbed as a whole unit of the energy (hf) by the electron in the metal. This is Einstein's hypothesis of energy quanta.

II. Albert Einstein (optional)

Albert Einstein (1879 – 1955) was not particularly brilliant in his formal schooling period. He found the German schools of the day to be too rigid and militaristic. He dropped out of school and went to Switzerland where he eventually graduated from the Zurich Polytechnic School in 1902. He went to work for the Swiss Patent Office in Bern, Switzerland where he evaluated patent applications in terms of their agreement with the laws of physics. During his spare time he thought about and worked on scientific problems.

In 1905, he published three papers on topics relevant to the world of Physics. The first paper was on the mathematics associated with **Brownian motion**. The second paper was on the **photoelectric effect**. The third paper was devoted to **special relativity**. Any one of the papers could have placed him in line for a Nobel Prize in Physics. Einstein, like Maxwell, was a theoretical genius and he would rely on other experimental scientists to confirm his theoretical results. The impact of his papers was immense and they caused much controversy.

In 1905, Einstein was granted a PhD from Zurich for his contributions. In 1915, Einstein went on to publish another major paper on **general relativity**. From 1919 on he was head of the Kaiser Wilhelm Institute for Physics in Berlin. In 1933, with the rise of the Nazi Party in Germany, Einstein left Berlin, renounced his German citizenship, and traveled to Princeton in the United States. He became a member of the Institute for Advanced Studies, an institution where scientists are not required to publish articles or teach classes. Einstein finished his career at this institution.

III. Einstein and the photoelectric effect

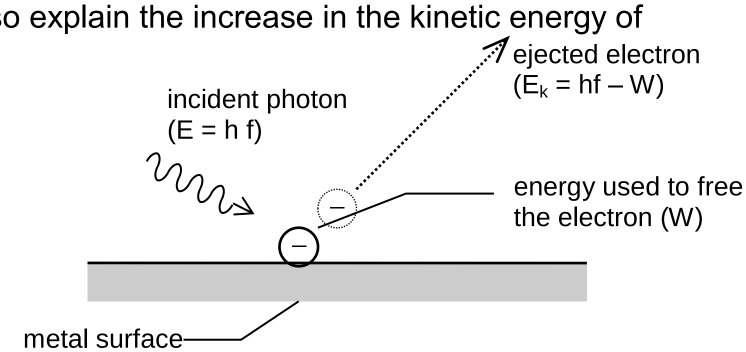
Einstein's explanation of the **photoelectric effect** borrowed from his mentor Max Planck. Einstein liked the concept of bundles of energy in matter and he expanded it to include any form of light energy which were later called **photons**. He believed that Planck was correct in assuming that the photons would have discreet amounts of energy and their energy could be calculated using

$$E = hf \quad \text{or} \quad E = \frac{hc}{\lambda}$$

In Einstein's explanation, he assumed that the electrons on the surface of a metal were held there with a certain amount of "binding" energy. For the electrons to become free of the metal, this binding energy had to be overcome. Einstein called the energy required to overcome the binding energy with the metal surface the **work function (W)**. Further, Hertz had discovered that light below a threshold frequency (f_o) would not free any electrons. The frequency of the light had to be at or above f_o. Using Planck's equation, Einstein could calculate the work function:

$$W = h f_o$$

If a photon with the threshold frequency strikes an atom of the metal, then an electron will be freed **immediately**. Thus Einstein was able to explain both the threshold frequency requirement and the instantaneous flow aspect of the photoelectric effect. In addition, Einstein's model implies that if you increase the number of photons striking the metal surface (increased **intensity**) you will get an increase in the number of photoelectrons bumped off the surface. An **increase in intensity produces a greater photocurrent**. Einstein's model can also explain the increase in the kinetic energy of the electron with an increase in the frequency of the incident light. If the incident photon possesses more than the minimum energy (W), any excess energy will be given to the escaping electron as kinetic energy. This can be written in a formula:



$$E_{K\ electron} = E_{photon} - W$$

Example 1

If the threshold frequency required for emission of a photoelectron is 4.00 x 10^{14} Hz, what is the work function of the surface in Joules and eV?

$$W = hf_o$$

$$W = 6.63\times10^{-34}\,J\cdot s(4.00\times10^{14}Hz)$$

$$W = \mathbf{2.65\times10^{-19}\,J} = \mathbf{1.66\,eV}$$

Example 2

If the work function of a metal surface is 3.00 x 10^{-19} J, and it is illuminated by light with a wavelength of 500 nm, what is the speed of the escaping photoelectrons?

$$E_{k\,electron} = E_{photon} - W$$

$$E_k = \frac{hc}{\lambda} - W$$

$$E_k = \frac{6.63\times10^{-34}\,J\cdot s(3.00\times10^{8}\,{}^{m}\!/\!_{s})}{500\times10^{-9}m} - 3.00\times10^{-19}\,J$$

$$E_k = 9.78\times10^{-20}\,J$$

$$E_k = \tfrac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E_k}{m}}$$

$$v = \sqrt{\frac{2(9.78\times10^{-20}\,J)}{9.11\times10^{-31}kg}}$$

$$v = \mathbf{4.63\times10^{5}\ {}^{m}\!/\!_{s}}$$

Example 3

A metal surface has a work function of 2.06 eV. If the fastest photoelectron emitted from is 6.00 x 10 ^{5} m/s, what is the frequency of the light source striking the surface?

$$E_k = \tfrac{1}{2}mv^2$$

$$E_k = \tfrac{1}{2}(9.11\times10^{-31}kg)(6.00\times10^{5}\,{}^{m}\!/\!_{s})^2$$

$$E_k = 1.64\times10^{-19}\,J$$

$$E_{photon} = E_{k\,electron} + W$$

$$hf = E_k + W$$

$$f = \frac{E_k + W}{h}$$

$$f = \frac{1.64\times10^{-19}\,J + 2.06eV(1.60\times10^{-19}\,{}^{J}\!/\!_{eV})}{6.63\times10^{-34}\,J\cdot s}$$

$$f = \mathbf{7.45\times10^{14}Hz}$$

Example 4

If a metal surface has a threshold frequency of 4.00 x 10^{14} Hz, what is the kinetic energy of the escaping photoelectrons when light with a frequency of 6.00 x 10^{14} Hz strikes the surface?

$$E_{k\,electron} = E_{photon} - W$$

$$E_k = hf - hf_o$$

$$E_k = h(f - f_o)$$

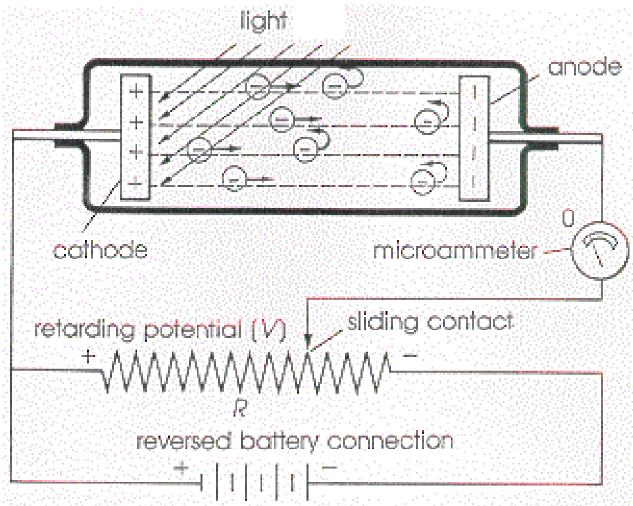
$$E_k = 6.63\times10^{-34}\,J\cdot s(6.00\times10^{14}\,{}^{1}\!/\!_{s} - 4.00\times10^{14}\,{}^{1}\!/\!_{s})$$

$$E_k = \mathbf{1.33\times10^{-19}\,J}$$

Einstein's explanation of the photoelectric effect could explain all the features discovered by Hertz, but it would require the experimental genius of R.A. Millikan to verify Einstein's theory.

IV. Millikan's photoelectric experiment

Millikan set up an experiment that would allow him to measure the energy of the escaping electrons while he varied the frequency of the incident light source. He set up the photoelectric tube so that a **reversed voltage** could be applied across the anode and cathode which would stop the ejected photoelectrons from reaching the anode.



With the voltage set up in the opposite direction, Millikan could make the other electrode so negative that it would repel the photoelectron and prevent its movement across the tube. He called the necessary voltage the **cut off** or **stop voltage**. Thus, the electric potential established would have the same energy as the escaping photoelectron.

$E_{k\ \text{electron}}$ = electric potential energy

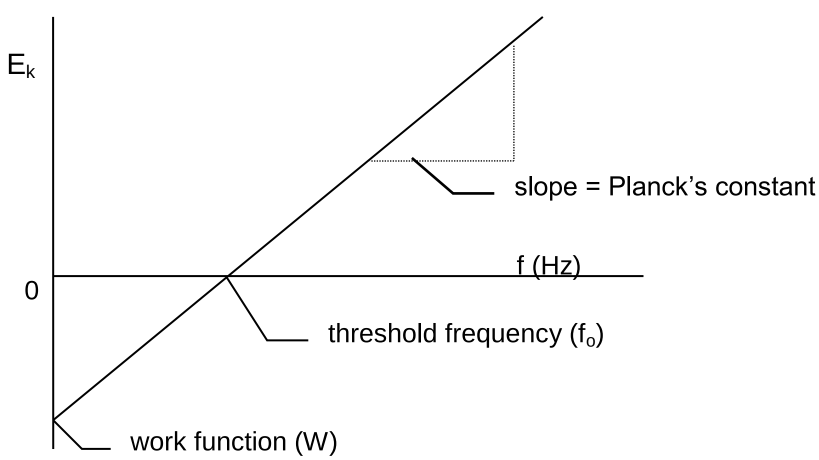
$E_k = q\,V_{stop}$

Millikan now had a practical way to measure the energy of the photoelectrons by raising the voltage until the current across the tube stopped flowing. In this way he could measure very accurate values of the kinetic energy of the photoelectrons for different light frequencies.

Millikan noted that Einstein's equation had the same structure as the general equation for a **straight line**:

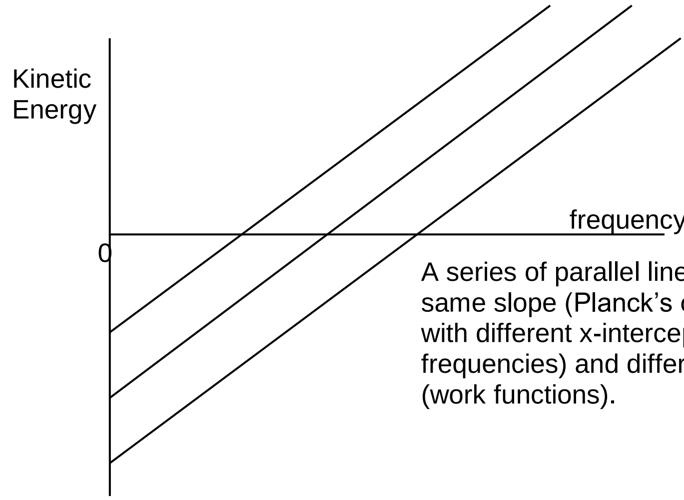
$$E_k = h\,f - W$$
$$y = m\,x + b$$

$x = f$ (horizontal axis)
$y = E_k$ (vertical axis)
$m = h$ (slope)
$b = -W$ (y intercept)



When Millikan plotted his data he found that the **slope** of the line did indeed equal **Planck's constant**. He also found that the **y-intercept** was the metal's **work function** and the **x-intercept** was the **threshold frequency** for the metal.

Millikan then used different metals and plotted the data the same way. He found that each metal gave a different line but each line had the same slope.



A series of parallel lines, all with the same slope (Planck's constant), but with different x-intercepts (threshold frequencies) and different y-intercepts (work functions).

Millikan's work in 1916 led to the awarding of three Nobel Prizes in Physics. The first was awarded to Max Planck in 1918 for the quantum theory of thermal radiation. The second was to Einstein in 1921 for the explanation of the photoelectric effect and the third was to Millikan for his work on the oil drop experiment plus the verification of Einstein's theory in 1923.

Example 5

If the stopping voltage in a certain photoelectric effect is 10.0 V and the incident wavelength of the light source is 105 nm, what is the work function of the metal surface?

$$E_{k\,electron} = E_{photon} - W$$

$$qV_{stop} = \frac{hc}{\lambda} - W$$

$$W = \frac{hc}{\lambda} - qV_{stop}$$

$$W = \frac{4.14\times10^{-15}\,eV\cdot s(3.00\times10^{8}\,{}^{m}\!/\!{}_{s})}{105\times10^{-9}\,m} - 1e(10.0V)$$

$$W = \mathbf{1.83\,eV} \text{ or } \mathbf{2.93\times10^{-20}\,J}$$

Note that this problem can be solved using either eV or J as the unit of energy. I chose to use eV and therefore I chose the appropriate Planck's constant and charge for e^-.

Every metal has its own work function value. Some examples are:

metal	work function (eV)
aluminum	4.25
barium	2.48
cadmium	4.07
calcium	3.33
cesium	1.90
copper	4.46
mercury	4.50
nickel	5.01
potassium	1.60
sodium	2.26
tungsten	4.52
zinc	3.31

V. Practice problems

1. If the threshold frequency required for photoelectron emission is 400 THz:
   A. What is the work function? (2.65×10^{-19} J)

   B. If the surface is illuminated by light with a wavelength of 500 nm, what is the speed of the escaping electrons? (5.40×10^{5} m/s)

   C. What is the stopping voltage for the photoelectrons? (0.829 V)

VI. Hand-in assignment

1. Monochromatic light of wavelength 500 nm falls on a metal cathode to produce photoelectrons. The intensity of the light at the metal surface is 100 Joules/m^2/s.
   A. What is the energy of a single photon of this light? (3.98×10^{-19} J)
   B. How many photons fall on one square meter in one second? (2.51×10^{20})
   C. If the cathode is a square which is 5.00 cm on a side, how many electrons are being released per second, assuming that every photon releases one photoelectron? How big a current would this produce?
   (6.28×10^{17}, 0.101 A)

2. For the photoelectric effect, explain what happens (and why):
   A. To the photocurrent as the light intensity increases.
   B. To the photocurrent as the frequency of the light is increased.
   C. To the speed of the photoelectrons as the radiation intensity increases.
   D. To the speed of the photoelectrons as the radiation frequency increases.

3. If the work function of a particular metal is 2.0 eV, what is the threshold frequency? (4.8×10^{14} Hz)

4. What is the maximum wavelength of radiation that causes photoelectric emission from a surface whose work function is 4.6 eV? (2.7×10^{-7} m)

5. A material has a threshold frequency of 1300 THz and is exposed to radiation which has a wavelength of 170 nm. What is the maximum kinetic energy of the ejected electron? If light with a wavelength of 300 nm is used, what is the kinetic energy of the ejected electron?

6. A material has a work function of 2.55 eV. If electrons are being emitted with a speed of 4.20×10^5 m/s, what is the wavelength of the incident light? (407 nm)

7. Radiation with a frequency of 752 THz is used to illuminate a photoelectric surface. If the work function is 2.20 eV, what retarding voltage must be applied to reduce the photocurrent to zero? (0.916 V)

Photoelectric Effect Online Activity

Access:
- Go to http://www.colorado.edu/physics/phet/web-pages/simulations-base.html .
- Click on the "Photoelectric Effect" simulation and begin the activity.

Purpose:
The goals of this activity are:
- ⇒ To visually experience the effects of changing frequency and changing intensity for the photoelectric effect.
- ⇒ To graphically determine the threshold frequency, work function and Planck's constant for several metals using a photoelectric effect applet.

Procedure:

The effect of frequency and intensity:
1. Before you begin, play around with the adjustable variables in the lab just to get a good feel for what the applet can do. Play with the intensity setting, wavelength setting, and voltage setting to see what Hertz noticed when he determined the basic principles of the photoelectric effect. (Note that you can click on the wavelength, intensity and voltage and enter the value that you want.)
2. Answer the following questions:
   - ⇒ What is the effect of higher frequency on the photocurrent?
   - ⇒ What is the effect of higher frequency on the kinetic energy of the photoelectrons?
   - ⇒ What is the effect of higher intensity on the photocurrent?
   - ⇒ What is the effect of higher intensity on the kinetic energy of the photoelectrons?

Millikan's experiment:
1. Choose a metal from the "Target" list.
2. Start by setting the "Beam Control" to 50%.
3. Adjust the wavelength so that the target metal is just emitting photoelectrons. Calculate the frequency of the light. This frequency represents the threshold frequency (f_o). Record this frequency in the data chart below. (You will compare this value to the value you obtain from your graph.)
4. Choose a wavelength and then adjust the stop voltage so that the photoelectrons come as close to (but without touching) the anode. Record these values in your chart.
5. Pick another shorter wavelength (there should be a minimum difference of 50 nm between them) and repeat step 4. Repeat until you have at least 4 data points.
6. Repeat steps 3 to 5 for **two** separate metals. From the information you have gathered determine the following:
   - ⇒ the kinetic energy of the photoelectrons using the recorded stop voltages (show one sample calculation).
   - ⇒ the frequencies of light using the recorded wavelengths of light (show one sample calculation).

7. In "Millikan like" fashion, create graphs of E_k vs. f for each metal on the same sheet of graph paper. Extrapolate the line of best fit to determine the following:
   - ⇒ the threshold frequency (f_o) for each metal (compare it to your recorded value)
   - ⇒ the work function of each metal
   - ⇒ Planck's constant (compare it to the accepted value of 6.63×10^{-34} J·s or 4.14×10^{-15} eV·s by calculating the percent error)

Observations:

Trial #1:
Metal: ____________________
Threshold wavelength: _______________ converted to frequency _______________

Measurement #	Wavelength (λ) (nm)	Frequency (f) ($\times 10^{14}$ Hz)	Stop Voltage (V_{stop}) (V)	Kinetic Energy (E_k) ( )
1				
2				
3				
4				

Trial #2:
Metal: ____________________
Threshold wavelength: _______________ converted to frequency _______________

Measurement #	Wavelength (λ) (nm)	Frequency (f) ($\times 10^{14}$ Hz)	Stop Voltage (V_{stop}) (V)	Kinetic Energy (E_k) ( )
1				
2				
3				
4				